A STUDY OF TURBIDITY MEASUREMENTS

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CHAPTER I

INTRODUCTION

A turbid liquid is one which appears muddy, cloudy, or opaque. This appearance is caused when light is scattered by the suspended particles. The turbidity of a liquid has long been a gauge of purity. It is reported that Bacon (1), in 1626 expressed surprise that any good could come from a turbid liquid.

The turbidity, τ, of a system is defined as the conservative absorption coefficient in the expression

$$I = I_0 e^{-\tau b} \qquad (1\text{-}1)$$

where I_0 is the intensity of the incident light, I is the intensity of the transmitted light, τ is the turbidity, b is the cell path in centimeters, and e is the mathematical symbol for 2.7183... (2,3). Frequently the relation is written as:

$$\tau = \frac{2.303}{b} \log_{10} \frac{I_0}{I} = \frac{2.303}{b} A \,. \qquad (1\text{-}2)$$

The turbidity of a system can be determined by both light transmission and light scattering measurements. The unit of turbidity is the reciprocal centimeter, $cm.^{-1}$.

History of Turbidity Measurements

The first measure of turbidity was made by the lowering of sand bags into the turbid media, and then recording the depth at which the bags disappeared (4). The terms used to describe a turbid suspension were "very slight," "slight," "distinct," and "decided" (5).

In 1889 the experiment station of the Massachusetts State Board of Health developed a method of turbidity measurement based on the disappearance of a submerged pin on a wooden staff (6). This was the basis for all of the disappearing wire methods. The platinum wire method, which was the standard for many years, used a platinum wire on a rod, and it was also based on this method (7,8).

Diaphanometers were used in the early experiments for determining turbidity. The diaphanometer was an instrument with a long-glass tube supported over either a flame or a spot. The turbid suspension was poured into the tube until the flame disappeared. The turbidity was inversely proportional to the depth of the suspension. In 1899 Parmelee and Kilne (9) described an improved diaphanometer. The improvement was the substitution of a cross for the spot. The reciprocal of the depth in inches was taken as the turbidity reading. This value agreed with the value found by the platinum wire method. In 1899 another early photometric device for the determination of the turbidity of a suspension was described by James Seddon (10).

In 1900 Daniel D. Jackson (11) developed a flame extinction diaphanometer for measuring sulfates in water. The instrument was adapted to determine turbidities of 100 parts per million (ppm) or larger. Today this instrument is commonly used in practically the same

form as Jackson's original design except that it is now calibrated to read turbidities as low as 25 ppm. This instrument is described in detail in Standard Methods for the Examination of Water, Sewage, and Industrial Wastes (12), and is the official method for measuring turbidity in the water works industry today.

In 1928 Venkataramanan (13) reported a new method for determining turbidity in small samples. It depended on the lowering of a coin into the medium and observing the disappearance of the letters on the coin.

The measurement of low turbidities continues to present a problem. In 1896 George Hornung (14) was reported to have used a diaphanometer type instrument for measuring low turbidities. The prevailing practice in 1920 was to look at a sample of water in a 1-gallon bottle and to compare it with bottled samples which contained suspensions of known turbidities (15). The next improvement was the installation of submerged lights in the storage basins. If the submerged light is in an ideal location in the basin it is a very sensitive method for detecting turbidity (15). In 1923 Baylis developed the Baylis Turbidimeter for the measurement of low turbidity (16). This is a comparison-type instrument based on scattered light. It is equipped with 30-inch tubes for reading turbidities between 2.0 and 0.0 ppm of suspended clay. In 1930 Graf and Holte (17) developed the Saint Louis Turbidimeter for reading low turbidities. The principle is similar to the Baylis instrument except that the tubes are only 15 cm. in length and the range is wider.

The Patterson Engineering Company of England has a convenient instrument, the Patterson Turbidimeter (18). This instrument has the

advantage that no standard is required because the turbidity is read directly from the scale on the instrument and is based on the reflectance of the sample.

In 1946 Hirsch (19) reported on the direct reading Hellige Turbidimeter which is based on the balancing of two different optical effects on the sample itself, the transmission and the scattering of light.

With the advent of the phototube and the photomultiplier tube many filter photometers and spectrophotometers have appeared on the market. Many of these instruments have been adapted to measure turbidity (20). A few of these are: Photovolt's Lumetron Model 450; Bausch and Lomb's Spectronic 20; Beckman's DU, B, DB, and DK-2 models; Coleman's photometer and nephelometer; Fisher's Electrophotometer; Phoenix Precision Instrument Company's Brice-Phoenix Light Scattering Photometer; and Perkin Elmer's Spectrecord. These instruments have the advantage that the detector is not the human eye (21). Fatigue effects and human error are eliminated. Furthermore calibration charts can be made for the individual instrument.

Shortly after 1930 there was considerable controversy in England about defining the scale of turbidity in terms of absorbance. Aitken and Mercer (22) favored the definition that the turbidity, T, be defined as follows: $T = 10^3 E / D$ where E is the extinction value and D is the cell depth. Knight (23) was in favor of having it stated that a certain cell path should be used to eliminate errors, especially errors incurred by using a short cell path. The latest suggested English definition is "The unit of turbidity is to be taken as that of a

suspension having an optical density of 0.001 per cm. depth to yellow light of a peak wave length of 580 mμ (24).

In 1954 Schultze-Mathka (25) suggested measuring the turbidity of oils by using the ratio of the intensity of the light transmitted by the suspension to the intensity of the light scattered by the suspension at an angle a, where a was not 90 degrees. The intensities of the light were measured with two photocells.

In 1957 Conley and Pitman (26) reported on a microphotometer for measuring low turbidities. It is reported to be able to detect turbidity in distilled water. The instrument is a relative turbidimeter, which is extremely sensitive, and is standardized by using Ludox and bentonite suspensions. Unfortunately, since it uses a mercury lamp without monochromators, it cannot be used for determinations involving organic polymers.

In 1958 Bernhardt, Bis, and Hoffmann (27) proposed two methods for the measurement of turbidity. The first method was to measure the light absorbed by the suspension, filter the suspension twice through millipore filters with suction, and remeasure the light absorbed by the suspension. The difference in the absorbed light was attributed to the turbidity of the suspension. The second method measured the forward scattering of the suspension at an angle of 10 degrees. From this measurement the turbidity was obtained.

In 1961 Meehan and Beattie (28) reported an absolute method of turbidimetric analysis. This method removed the empirical comparison and is based on the measurement of turbidity at an experimentally determined wave length. The observed turbidity is proportional to the

reciprocal of the wave length. The observed turbidity was related to the weight concentration through the Mie scattering coefficient. It is necessary to determine the desired wave length by light scattering techniques.

History of Water Analysis Turbidity Standards

In 1900 Mason (29) suggested the use of a kaolin suspension, containing 1 gram of clay in 1 liter of water. This was the first suggestion of a standard suspension. Whipple and Jackson (30) improved the method by substituting finely powdered diatomaceous earth for the kaolin in order to have a more reproducible standard.

In 1901 the committee on Standard Methods of Water Analysis of the American Public Health Association (31) recommended that the turbidity produced by 1 ppm of silica be considered the standard unit of turbidity. This was the first definite standard used in America.

In 1902 the standard adopted by the United States Geological Survey (32,33) fixed the turbidity scale for the platinum wire method. This was the basis for the "silica scale" and the "parts per million scale which lasted until about 1930. P. V. Wells (7) and Baylis (3), and many other authors have quoted the method in detail from the circular. Briefly, a water of 100 had 100 ppm of silica. The fineness of the silica was determined because the 1-millimeter diameter platinum wire was to be barely visible at a depth of 100 millimeters. The observer was to be 1.2 meters above the wire and the vessel was to be large enough that the sides did not shut out light and influence the results. The final requirement was that the observation should be made in the middle of the day, in open air, but not in direct sunlight. This

report also gave the scale for the United States Geological Survey turbidity rod of 1902.

In 1923 Baylis (16) recommended using suspensions of fullers earth for use as standards with the Baylis Turbidimeter. In 1943 Theroux, Eldridge, and Mallmann (34) recommended as standards either a suspension of fullers earth or of bentonite. The recommended method of preparation is to add an excess of the clay to a liter of water, shake well, allow to stand overnight, and then to withdraw the supernatant liquid into another bottle without disturbing the sediment on the bottom. The supernatant liquid was the standard and the turbidity was determined with the Jackson Candle Turbidimeter. This standard was then diluted to the desired values.

In 1930 de Loureio (35) reported using barium sulfate in glycerol as a turbidity standard. He assumed that the glycerol stabilized the suspension by stabilizing the particle size.

In 1943 Hallimann (36) reported using a suspension of pyrex. The suspension was prepared by shaking freshly broken pyrex chips in a pyrex bottle until the suspension appeared as a 'dilute skim milk.' The 'dilute skim milk' was allowed to stand and the decantate was used as the standard.

From 1954 to 1957 the Society of Brewing Chemists (37,38) studied the problem of determining the turbidity in beer. In 1957 the final report recommended that the standard be a suspension of formazin which is the crosslinked polymer formed when hydrazine sulfate is added to hexamethylenetetramine.

Several authors have reported using Ludox as a standard (3,39-44). Ludox is a suspension of colloidal silica which is prepared by E. I. du Pont de Nemours and Company and is very stable. The dilutions are also very stable.

In 1957 Rodier and Fairve-Dubos (43) reported the use of a "resine de mastic' prepared by the method of Dienert and modified by Grimmald and Morand (46). Rodier and Fairve-Dubos also modified the American silica scale. Neither scale seemed entirely satisfactory and they recommended reporting turbidities as relative concentrations.

Dubya (47) recommended using a polystyrene latex for light scattering standardizations. These latexes have been studied in detail (39,40,48-60) and one source is the Dow Chemical Company. One big advantage of the Dow polystyrene latexes is that the particle diameter range is small and is a known value.

In 1958 Fikhman (61) reported preparing stable turbidity standards from methyl methacrylate-polystyrene and benzoyl peroxide. The polymer is prepared by heating on a water bath with constant stirring.

Purpose of This Study

This varied picture indicates that a standard method for the measurement of trace turbidities in water has not yet been established. In fact, several intensive studies have been begun, but unfortunately have never been completed (4,7,14). The purpose of this study is to compare several standards and many instruments with the hope of finding both a suitable standard and a suitable method for determining the turbidity.

CHAPTER II

THEORY

When light enters a solution it is reduced in intensity. This loss in intensity occurs in several ways. First, some of the light is reflected by the change of medium, i.e., the optical faces of the solution cell reflect the light. This is caused by the difference in refractive index of the solution, the cell, and the surrounding medium. The decrease in intensity due to the reflection is not as significant as the other factors. Second, the solution may not be transparent to the radiation and the absorbed radiation promotes energy changes within the ions and molecules. Third, the solution will also scatter the incident beam if large ions and molecules are present. Both the intensity of the absorption and the intensity of the scattering are dependent on the wave length of light entering the solution. The turbidity of the solution may be measured by either the intensity of the scattered light or by the intensity of the transmitted light.

Light Scattering

The study of scattered light was first reported by Tyndall (62) in 1869. In 1871 Rayleigh (63) stated the following relation for light scattering:

$$\frac{i}{I} = \frac{8 \pi^4 v a^2}{(\lambda')^4 r^2} (1 + \cos^2 \theta) \qquad (2\text{-}1)$$

where i is the intensity of scattered light per unit volume, I is the intensity of the incident beam, v is the unit volume of the scattering system, r is the distance of the observer from the scattering system, θ is the angle between the observer and the proceeding incident beam, λ is the wave length of the incident light, n is the refractive index of the medium, and λ' is the wave length of light falling on the particles, where λ' is the ratio λ/n. For θ = 90 degrees the turbidity, τ, has been defined by Born (64) as:

$$\tau = \frac{16}{3} \pi r^2 \frac{i}{I} . \qquad (2-2)$$

By substituting equation (2-1) into equation (2-2) the turbidity may be expressed as:

$$\tau = \frac{128 \pi^5 v a^2}{3 (\lambda')^4} . \qquad (2-3)$$

In order to relate equation (2-3) to experimental quantities it is necessary to introduce some optical constants. For a mixture of isotropic particles of a given polarizability immersed in a medium with a given dielectric constant the following relation holds:

$$\frac{\epsilon - \epsilon_0}{\epsilon} = 4\pi v \alpha \qquad (2-4)$$

where ϵ_0 is the optical dielectric constant of a transparent material and is equal to the square of the refractive index of the material, and ϵ is the optical dielectric constant of the mixture. Equation (2-4) holds regardless of the size, or shape of the particles and makes no

assumptions. By substituting equation (2-4) into equation (2-3) the turbidity can be expressed as:

$$\tau = \frac{8\pi^3 (n - n_0)^2}{3 \lambda^4 v} . \qquad (2-5)$$

It is known that $v = N c/M$ where N is Avogadro's number, c is the weight concentration and M is the molecular weight. By substituting this value for v into equation (2-5)

$$\tau = \frac{8 \pi^3 M c}{3 \lambda^4 N} \left(\frac{n - n_0}{c} \right)^2 . \qquad (2-6)$$

Since $\left(\frac{n - n_0}{c} \right) = 2 n_0^2 \left(\frac{n - n_0}{c} \right)^2$, where n_0 is the refractive index of the solvent, equation (2-6) may be expressed as:

$$\tau = \frac{32 \pi^3 n_0^2}{3 N \lambda^4} \left(\frac{n - n_0}{c} \right)^2 c M . \qquad (2-7)$$

$$\tau = M K c \qquad (2-8)$$

if $$\frac{32 \pi^3 n_0}{3 N \lambda^4} \left(\frac{n - n_0}{c} \right)^2 \qquad (2-9)$$

is expressed as the constant K. These relations hold only for the turbidities of small particles where the diameters are less than $\lambda / (|n - 1|)$ (65) and the relative refractive index, n, is close to one. The relative refractive index is defined as the ratio n/n_0 (66).

In 1908 Mie (67) proposed a general equation for the scattering of light. This has been modified by Debye (68), Rayleigh (69), Gans (70),

Moglich (71), Jobst (72), and Zinn (73). Heller, et al. (48,54) have calculated many of the Mie functions. Some of the general classifications follow for the cases where x is defined as $2\pi r/\lambda$, and m is the relative refractive index: (1) If $mx \rightarrow 0$, then the Mie equation reduces to the Rayleigh Ratio (2-1). (2) If $m \geq 1.3$ and $x \geq 1$, then the equation and calculations are very lengthy. (3) If $m = 1.3$ and $x = 1$, then the Mie series can be expressed with sufficient accuracy as the sum of terms involving the contribution to scattering by the magnetic dipoles moments, the electric dipole and quadrapole moments. (4) If m is approximately one, then for particles with a dimension equal to the wave length of light, or greater, each volume element of the particle will scatter light according to the Rayleigh Ratio (2-1). For this region the Rayleigh-Gans theory (69,70) is best.

Turbidity as given by equation (2-2) and by equation (2-8) is termed as the relative turbidity, and it may vary from instrument to instrument for a given suspension. Brice, et al. (2) have developed an instrument for measuring absolute turbidities.

The absolute turbidity varies from the relative turbidity by several correction factors. The actual irradiance, I_s, at the phototube diffusor, after inserting appropriate factors for effects resulting in losses and gains in irradiance, is:

$$I_s = \frac{3\,(1.045)\,I_0\,\tau(W_s L\,h)\,T_s}{16\pi r^2\left[1 - (b/r)(n-1)/n\right]^2 n^2} \quad . \qquad (2\text{-}10)$$

Included are: the refraction factors, $\left[1 - (b/r)(n-1)/n\right]^2 n^2$, a factor 1.045 to adjust for the effective increase in irradiance due to

the reflection of a portion of the transmitted beam on emerging from the scattering cell, the reduced volume contributing to the scattered radiation, the reduced volume is defined by $W_s L\, h$ where W_s is the width, L is the length, and h is the depth; and a factor T_s, the transmittance of the filled scattering cell, to account for losses by surface reflections and attenuations by scattering and by solvent absorption. The irradiance at the phototube diffusor (with the compensating cell in place) is:

$$I_s = \frac{I_0 \, (W_s L) \, T \, D \, T_c}{\pi r^2 \left[1 - (b/r)(n-1)/n\right]^2} \qquad (2\text{-}11)$$

The correction factors in this case are: The factor for the foreshortening of r, $r^2 \left[1 - (b/r)(n-1)/n\right]^2$; the reduced area, $W_s L$, contributing radiation to the receiver: a factor T_c, the transmittance of the filled compensating cell to account for losses by surface reflections and attenuations by scattering and by solvent absorption; a diffusor correction, D, to adjust for deviation of the standard opal glass from a perfect diffusor.

By dividing equation (2-10) by equation (2-11), I_s/I_s, the ratio of irradiances at the phototube diffusor for the scattering suspension and the standard diffusor, is obtained. In equation (2-10) and (2-11) it has been assumed that h, W_s, and L are small compared with r, and some of the integrations used in developing the correction factors are for limited volume elements. Solving for turbidity in the equation for I_s/I_s gives:

$$\tau = \frac{16 \, n^2 \, T \, D \, T_c I_s}{3(1.045) h \, T_s I_s} \, . \qquad (2\text{-}12)$$

I_s/I_s can be replaced by FG_s/G_s, the ratio of the galvanometer deflections multiplied by the transmittance of the neutral filter or filters used when reading G_s. The final geometric factor of the equation is h, the depth of the beam. The ratio of the transmittances, T_c/T_s, has not been convenient. In this method the ratio T_c/T_s may be replaced by the value aR_w/R_c, where a is a constant and R_w/R_c is the residual refraction correction which is a constant for a given solvent. Making the above substitutions in equation (2-12):

$$\tau = \frac{16\, n^2 T\, D\, a\, R_w\, F\, G_c}{3(1.045)h\, R_c\, G_s} \quad . \qquad (2\text{-}13)$$

This equation is used to relate the galvanometer deflections to the absolute turbidity in the Brice-Phoenix Light Scattering Photometer (74).

The amount of light transmitted is that portion of the incident beam which reaches the detector. In other words the transmitted light is that which is left, or $I_t = I_0 - (I_s + I_a + I_r)$ (2-14)

where I_t is the intensity of the transmitted light, I_0 is the intensity of the incident beam, I_s is the intensity of the scattered light, I_a is the intensity of the absorbed light, and I_r is the intensity of the reflected light.

If a monochromatic beam of light of intensity I_0 passes through a solution thickness db, the intensity of the transmitted light will be $I_0 - dI_1$. This process may be continued many times, and the ratio of the absorbed intensity to the incident beam will be constant. As db

approaches zero the decreases in light transmitted become equal, and the amount of light transmitted becomes approximately equal because dI will be small compared to I_0. The value $-dI/I_0$ is proportional to the number of absorbing centers per cubic centimeter of solution. If q is a proportionality constant dependent on the wave length of light then

$$-dI/I_0 = q\, dN . \qquad (2\text{-}15)$$

Integrating equation (2-15) with the limits where I varies from I_0 to I_t and N varies from 0 to N, then

$$\ln (I_0/I_t) = q N . \qquad (2\text{-}16)$$

Equation (2-16) is known as either the absorption law or Beer's Law (75).

The number of centers in a given volume of unit cross sectional area is given by

$$N = c_m N_0 b \times 1 \text{ cm.}^2 \qquad (2\text{-}17)$$

where c_m is the concentration in moles per cubic centimeter, N_0 is Avogadro's number, i.e., 6×10^{23}, and b is the cell length in centimeters. Let

$$\tau = c_m N_0 q \times 1 \text{ cm.}^2 , \qquad (2\text{-}18)$$

By substituting equations (2-17) and (2-18) into equation (2-16) and changing to common logarithms the equation becomes:

$$2.303 \log (I_0/I_t) = \tau b . \qquad (2\text{-}19)$$

In order to obtain an expression for turbidity in terms of the intensity of the transmitted light, equation (2-19) is solved for τ.

$$\tau = \frac{2.303}{b} \log \frac{I_0}{I_t} \quad . \qquad (2\text{-}20)$$

The term $\log (I_0/I_t)$ is known as the absorbance, A. Substituting A into equation (2-20) gives an expression for turbidity in terms of A.

$$\tau = \frac{2.303\ A}{b} \quad . \qquad (2\text{-}21)$$

Equation (2-20) and (2-21) are the same equation as (1-2).

From equation (2-21) it is noted that the turbidity is directly proportional to the concentration at a given wave length. For a given b, $\tau = K A$, and A varies directly with τ. This suggests a convenient measure of concentration by turbidity. A plot of A versus c or τ versus c yields standard curves. Doty and Steiner (76) have introduced Q, the particle dissipation factor, which is a factor to correct the observed turbidity to the value it would have been in the absence of interferences. Q characterizes the ability of the particles to dissipate light from the incident beam and is useful in correcting turbidities of more concentrated suspensions.

Rose and Lloyd (77) have derived an expression for $\ln (I_0/I_t)$ which takes into account the surface area of the particle and the area unobstructed by particles:

$$\ln \frac{I_0}{I_t} = \bar{k}_2 \, a \, b \sum_{i = dz_1}^{dz_2} n \, d_i \qquad (2\text{-}22)$$

where $\bar{k}_2$ is the average of the opacity factor, c is the concentration in grams per cubic centimeter, b is the path length in centimeters, n is the number of particles, d is the diameter of the particle in centimeters, Z_1 is the smallest particle, and Z_2 is the largest particle. If A_p is the projected area of all particles, then

$$A_p = c \bar{k}_2 \sum_{i=dZ_1}^{dZ_2} n d_i . \qquad (2\text{-}23)$$

By substituting A_p in equation (2-22), the equation becomes

$$\ln (I_0/I_t) = A_p b. \qquad (2\text{-}24)$$

By eliminating $\ln (I_0/I_t)$ between equations (2-19) and (2-24), the result is $\tau b = A_p b$, or $\tau = A_p$. This relation indicates that the turbidity is equivalent to the projected area of all of the particles in suspension. This relation assumes that no particle is in the shadow of another particle.

These relations of turbidity and transmitted light are limited to colorless turbidity unless it has been determined that the color absorbing species does not absorb at the wave length of light used for the turbidity measurements. In the case of colorless turbidity the amount of light absorbed is negligible and the transmitted light is directly related to the amount of scattered light. Equation (2-14) reduces to

$$I_t = I_0 - I_s \qquad (2\text{-}25)$$

for colorless turbid suspensions.

Refractive Index

At first glance the refractive index appears to be a good measure of the turbidity. However, since the ratio $(n - n_0)/c$ is constant for any solvent-solute system (78), the refractive index is not a quantitative measure of the turbidity.

Variation of Wave Length

The scattering ratio is known to be a function of the particle size (7,8,66 79). By varying the wave length of light the scattering ratio varies inversely as the yth power of the wave length as shown by the general equation (80):

$$I_s/I_0 = k\,c\,x\,r^2\,(r/\lambda)^y \quad , \qquad -2.2 \leq y \leq 4 \qquad (2\text{-}26)$$

where k is a constant, c is the concentration, x is the depth of the suspension, r is the radius of the suspended particles, λ is the wave length of light used in making the measurement, and y depends on the size of the suspended particles. The exponent y decreases as r increases. All of the proposed equations are an attempt to describe what is occurring in the system. The value of y is constantly changing with the change in particle size and the whole integers are just approximations.

Since $I_0 = I_t + I_s$, or $\frac{I_t}{I_0} = 1 - \frac{I_s}{I_0}$ for colorless turbid suspensions it is expected that as I_s increases, I_t will decrease. The quantity I_t/I_0 is approximately equal to e^{-I_s/I_0} since the quantity $(1 - x)$ is approximately equal to e^{-x}. Applying this relation to

equation (2-26) an equation for I_t/I_0 is obtained.

$$I_t/I_0 = e^{-k\,c\,x\,r^2\,(r/\lambda)^y}, \qquad -2.2 \leq y \leq 4, \quad (2\text{-}27)$$

or in terms of absorbance, equation (2-27) becomes:

$$A = k'\,c\,x\,r^2\,(r/\lambda)^y, \qquad -2.2 \leq y \leq 4. \quad (2\text{-}28)$$

Substituting equation (2-21) into equation (2-28) the expression for turbidity is (81):

$$= k''\,c\,r^2\,(r/\lambda)^y, \qquad -2.2 \leq y \leq 4. \quad (2\text{-}29)$$

Equation (2-29) indicates that the turbidity is dependent on both the size of the particle and on the wave length of light used in making the measurement. It also indicates that if the particle size, the wave length of light, and k'' remain constant then the turbidity should vary linearly with the concentration of suspended material.

The differences in particle size can be estimated by the comparison of the turbidities of a given material in equal concentrations. Information concerning the particle size may be obtained by means of the Mie theory by (1) observation of the transmitted light as a function of wave length, (2) measurement of the intensity of the scattered light at a given wave length, (3) determination of the color of the scattered light, and (4) determination of the polarization of the scattered light at a given wave length (82).

EXPERIMENTAL

[redacted]

Turbidimeters. Nine instruments were used to determine the turbidity of prepared suspensions.

A Brice-Phoenix Light Scattering Photometer Series 1965 produced by the Phoenix Precision Instrument Company was used to determine the absolute turbidity of the suspensions. It is equipped with a high pressure mercury vapor lamp type AH-3, 85 watts. Filters are used to isolate the various mercury lines and the detector is a photomultiplier tube. The photometer used in this research is equipped with a galvanometer with a sensitivity of 0.0015 μa/mm. The absorption cell used in this research was the 30 mm. by 30 mm. square cell.

A Beckman DK-2 Ratio Recording Spectrophotometer was used to determine the variation of turbidity with wave length for the suspensions. This instrument is equipped with both tungsten and hydrogen lamps and the photomultiplier tube was used exclusively as the detector. Both 5.001 and 9.997-cm. quartz absorption cells were used in making the [redacted]

A Beckman DU Quartz Spectrophotometer was used to determine the turbidity by transmission methods. The instrument used in this research was equipped with a tungsten lamp source and two phototubes (red and blue) which served as the detectors. This instrument was equipped with a

long cell compartment so that both 5 and 10-cm. absorption cells could be used. The power supply was a storage battery with a line operated charger which was furnished by the Beckman Instruments Co.

The following instruments were used to compare turbidity data for Table IX: a Beckman Model B Spectrophotometer; a Bausch and Lomb Spectronic 20; a Photovolt Corp. Lumetron Model 450; a Phipps and Bird St. Louis Turbidimeter, a Jackson Candle Turbidimeter, and a Hellige Turbidimeter.

The Jackson Candle Turbidimeter was used to determine the turbidity of the stock suspensions.

Balances. For all analytical weighings a Mettler Model B-6 Balance with an accuracy of $\pm$ 0.02 mg. was used. For rough weighings a triple beam Chaus laboratory balance was used.

Blendor. A Waring Blendor was used for blending certain of the clay samples.

Mill. A Wiley Mill, Model 2 equipped with a 100-mesh screen was used to mill the clay samples.

Sieve. A Tyler 325-mesh sieve was used to sieve the clay samples.

Centrifuge. An International Equipment Company Centrifuge operated at 1500 rpm was used to centrifuge some of the clay samples.

Irradiator. A Fisher Infra Radiator was used to evaporate the solvent for the determination of the total dissolved solids in the clay suspensions.

Shaker. A Precision Scientific Company shaker was used in the sieving of the clay samples and in the preparation of clay suspensions.

Electrodialysis cell. A plexiglass dialysis cell was used in the electrodialysis of the clays. This cell was equipped with a copper cathode and a graphite anode. Parchment paper was used as the membrane to separate the cell compartments.

Mixers. Mag-Mix magnetic stirrers were used throughout this research.

pH Meter. A Beckman Model G pH Meter was used for all pH determinations. Both a standard glass electrode and a blue tip glass electrode were used with the saturated calomel reference electrode.

Glassware. Normax pipettes and Normax, Pyrex Grade A, and Kimble Exax volumetric flasks were used in this research.

Refractometer. A Brice-Phoenix Differential Refractometer was used to determine the refractive indices of the suspensions.

[redacted]

Turbidity free water. The first problem was to obtain the water with the lowest possible turbidity. The method used to determine the relative quality of the water was to measure the absolute turbidity on the Brice-Phoenix Light Scattering Photometer. The waters investigated included: water distilled from the chemistry department still, boiled distilled water deionized water from a Permutit deionizer, boiled deionized water; triply distilled water produced by a Modal 3DSH-20 Barnstead Still, boiled triply distilled water, and Harleco turbidity free water sold by the Hartman-Leddon Co. The triply distilled water proved to have the lowest absolute turbidity and was used in all dilutions and preparations in this research.

TABLE I

Sources of Materials[a]

Material	Particle Diameter	Conc. in per cent	Lot Number	Source
Polystyrene Latex	88 mμ	10.00	LS-040-A	The Dow Chemical Co. The Midland Division
Polystyrene [redacted]	188 mμ	10.26	LS-055-A	The Dow Chemical Co.
Polystyrene Latex	264 mμ	10.00	LS-057-A	The Dow Chemical Co.
Polystyrene Latex	365 mμ	10.00	LS-061-A	The Dow Chemical Co.
Polystyrene Latex	537 mμ	9.92	LS-063-A	The Dow Chemical Co.
Polystyrene Latex	814 mμ	10.70	LS-066-A	The Dow Chemical Co.
Polystyrene Latex	1171 mμ	9.98	LS-067-A	The Dow Chemical Co.
Ludox	7 mμ	15.20	SM-1612038	E. I. du Pont de Nemours and Co., Inc.
Ludox	10-15 mμ	29.60	CC-3413-85	E. I. du Pont de Nemours and Co., Inc.
Fullers Earth Diluex	b	--	--	The Floridan Company
Volclay Bentonite	c	--	KMK	The American Colloid Company
Kaolinite	--	--	--	Edgar Plastic Company
Illite	--	--	36	Ward's Natural Science [redacted]
Turbidity Free Water	--	--	20001	Hartman-Leddon Company

TABLE I

Continued

Material	Particle Diameter	Conc. in per cent	Lot Number	Source
Turbidity [redacted]				
10 ppm	--	0.001	20001	Hartman-Leddon Company

[a]All common chemicals used in this study were of reagent grade.

[b]70-80 per cent pass a 325-mesh sieve.

[c]90-95 per cent pass dry 20 to 70-mesh sieve.

Suspensions of ionic compounds. Suspensions of silver chloride were prepared by adding a measured volume of 0.0028 M sodium chloride to a measured volume of 0.0028 M silver nitrate in triply distilled water in an Erlenmeyer flask. These suspensions were prepared in semidarkness, the turbidity measured, and the suspensions were then stored in the dark.

Suspensions of barium sulfate were prepared according to Standard Methods (83) by the dilution of measured amounts of 0.02 M sulfuric acid to 50 ml. in a 250-ml. Erlenmeyer flask. Exactly 10 ml. of acid-salt solution (4 M NaCl in 0.2 M HCl) was added to the sulfate and was mixed with a magnetic stirrer. Approximately 0.5 g. of barium chloride dihydrate crystals was added to the above solution and stirred for a definite period of time (from 45 sec. to 3 min.). The suspension was allowed to stand for exactly 4 minutes and the turbidity was then measured. The suspensions were stored in the flasks with rubber stoppers.

Suspensions of calcium carbonate were prepared by adding a weighed sample of Purecal U, precipitated calcium carbonate of a very fine particle size, into a volumetric flask, diluting to volume, shaking, and measuring the turbidity.

Suspensions of clays. Suspensions of the following clays were studied. Volclay Bentonite; Floridan Fullers Earth; Edgar Kaolinite; and Ward's Illite No. 36. The same procedures were followed for each of the clays.

All of the clays were prepared in the dry state as follows: The clay was milled to pass a 100-mesh screen, and then ground in an agate mortar with an agate pestle and sieved with a 325-mesh sieve. This sieved clay was used in all further steps in the preparation of the clay suspensions.

The first procedure was to add a weighed sample of clay to the desired volumetric flask, dilute to volume, shake, and read. The first modification was to blend the clay and water before the final dilution to volume. The next modification was to omit blending, and to shake at intervals before the final dilution to volume. After the final dilution to volume, the suspensions were again shaken and the turbidity was

It was hoped that the electrodialysis of clay, followed by the addition of sodium hydroxide to raise the pH to a value of 9 would produce a stable suspension. The clay was electrodialized until no change in current was observed over a 24-hour period. The electrodialized clay was then dried at 105 degrees C., ground, sieved, weighed, suspended in water, titrated with NaOH, and finally was diluted to volume.

Another recommended method of preparation of clay suspensions is to suspend an excess of clay in triply distilled water. The suspension is thoroughly shaken and is allowed to settle for 24 hours. The supernatant liquid is withdrawn, without disturbing the sediment on the bottom, and is used as the stock suspension. The weight concentration of the stock suspension is determined by evaporating a known volume to dryness.

For additional stability the clay stock suspension should be centrifuged to remove the larger remaining particles.

The stabilizing agents investigated in this study were potassium ferrocyanide and sodium hydroxide. The latter was used to raise the pH to a value above 9. The ferrocyanide was added, as a solution which contained a known weight per unit volume, in each dilution just before the final dilution. The pH was adjusted by diluting the suspension to a certain volume and then titrating to a pH of 10 with 0.1 N NaOH. The suspension was then diluted to the final volume. In order to obtain an equilibrium pH of 9 an excess of base must be present initially, since clays reach ionic equilibrium very slowly. Each clay suspension was allowed a 5 minute interval to come to equilibrium with the pH meter electrodes before the pH measurement was made.

It is recommended that the following procedure be used if clays are to serve as standards. Approximately 5 g. of the clay should be suspended in 2 liters of triply distilled water, shaken for 30 minutes, and allowed to settle for 24 hours. The supernatant liquid should be withdrawn without disturbing the sediment on the bottom. The supernatant liquid is then shaken and centrifuged for 15 minutes at 1500 rpm. The centrifugate is withdrawn without disturbing the sediment on the

bottom of the centrifuge tube and is labeled as the stable stock suspension. This stock suspension can be diluted as desired. In order to obtain the weight concentration a known volume of the suspension is evaporated to dryness and weighed. The following variations may prove to be necessary in special cases. In order to suspend the excess clay in water it may be necessary to blend for 1 minute to prepare an initial clay syrup of swelling clays. Certain stabilizing agents must be added in the dilution processes.

Suspensions of formazin. The formazin stock suspension was prepared by adding 25 ml. of 1 per cent hydrazine sulfate solution to 2.500 g. of hexamethylenetetramine in 25 ml. of triply distilled water. The mixture was stirred for 2 hours with a magnetic stirrer to increase the speed of polymerization. This stock suspension was then diluted with triply distilled water. In order to obtain the suspension known as 1000 FTU (formazin turbidity units), 29 ml. of the stock suspension was diluted to 2 liters. Similarly when 14.5 ml. of the stock suspension was diluted to 2 liters the suspension known as 500 FTU was obtained. Even more dilutions were obtained by further dilution.

Suspensions of polystyrene latex. Suspensions of polystyrene latex were prepared as follows: A known weight of the 10 per cent polystyrene latex stock was weighed into a small volumetric flask and then diluted to volume. Ten ml. of this turbid suspension was diluted with triply distilled water to 2 liters. Even more dilute suspensions were obtained by further dilution.

Suspensions of Ludox. Suspensions of Ludox were prepared by dilution of the concentrated stock suspension with triply distilled water.

Ludox suspensions in 0.05 M NaCl were also prepared. The only difference in the preparation was that the necessary weight of sodium chloride was added in the dry form to the volumetric flask before the addition of the Ludox.

Procedure Used in Filling Absorption Cells

In all measurements the absorption cell was washed three times with the solvent, triply distilled water, and then rinsed three times with the liquid to be measured before filling the cell with the liquid. The cell faces were first wiped with Kleenex tissue and then with lens paper. The cells were always placed in the same position in the instrument. The amount of scattering produced by the triply distilled water was taken as the criterion for the cleanliness of the light scattering cell. The limiting value was established as 6.0×10^{-5} cm.$^{-1}$ at 436 mμ. If additional cleaning was necessary the following procedure was used: The cell was first soaked for 3 minutes in 6 M HCl, rinsed with generous amounts of tap water, washed with detergent solution followed by successive rinsings with tap water, deionized water, and finally with triply distilled water.

Procedure for Stability Studies

The suspensions of formazin and of polystyrene latex were stored in carefully cleaned 2.5-liter pyrex glass bottles. The suspensions of Ludox and of the various clays were stored in carefully cleaned 2-liter polyethylene bottles. These suspensions were all stored at room temperature. The stability of the suspensions was determined by the absolute turbidity as measured with a Brice-Phoenix Light Scattering

Photometer. The suspensions were read at regular intervals depending on the suspension, previous stability data, and the information desired. The stability data are listed in Tables X to XXXIX.

[redacted]

Representative samples which contained approximately 3 ppm of suspended material were read on the following instruments: a Lumetron Model 450, a Spectronic 20, a Beckman Model B Spectrophotometer, a Beckman DU Quartz Spectrophotometer, a Beckman DK-2 Ratio Recording Spectrophotometer, a St. Louis Turbidimeter, a Hellige Turbidimeter, and a Brice-Phoenix Light Scattering Photometer. Turbidity was calculated in $cm.^{-1}$ and the results are shown in Table IX.

The variation of turbidity, as determined on a Beckman DU Quartz Spectrophotometer, with respect to concentration and to particle size is shown for the polystyrene latex samples in Figure 3.

[redacted]

The recommended method of the manufacturer for the determination of refractive indices using the Brice-Phoenix Differential Refractometer was followed.

CHAPTER IV

DISCUSSION OF RESULTS

[redacted]

The criteria for turbidity free water are that it have the lowest possible turbidity, that it be easily obtained, and that the turbidity remain constant. It was realized that no water is absolutely free of turbidity. Goring and Napier (84) reported an absolute turbidity at 546 mμ of 1.76×10^{-5} cm.$^{-1}$ for pure water. They attributed the turbidity to the fact that water molecules form scattering centers and that foreign particles, which scatter light, are always present. An absolute turbidity at 436 mμ of 2.5×10^{-6} cm.$^{-1}$ was obtained with air using the Brice-Phoenix Light Scattering Photometer. The waters investigated include Harleco turbidity free water, singly distilled water, boiled singly distilled water, deionized water, boiled deionized water, triply distilled water, and boiled triply distilled water. Table XI shows the data obtained at 436 mμ.

A sample of commercial turbidity free water was obtained from the Hartman-Leddon Co. (Harleco). This water had a turbidity value which was higher than the waters available in this laboratory.

Singly distilled water is piped into the laboratory. Both raw singly distilled water and boiled singly distilled water were studied. The fluctuations in the turbidity in the raw singly distilled water was within the range of experimental error, but the large increase in turbidity produced by boiling indicated the presence of impurities.

TABLE II

Turbidity in $cm.^{-1}$ of the Various Waters

Water	1 Day	1 Week	1 Month	4 Months	5 Months
Barlaco	0.000143	0.000153	--	--	--
Singly Distilled	0.000097	0.000076	0.000061	--	--
Boiled Singly Distilled	0.003000	0.004100	0.003190	--	--
Deionized	0.000090	0.000110	0.000148	0.000300	0.000380
Boiled Deionized	0.000120	--	--	--	--
Triply Distilled	0.000057	0.000054	0.000055	--	0.000062
Boiled Triply Distilled	0.000081	--	--	--	--

Both raw and boiled deionized water from a Permutit deionizer were studied. The increase in the turbidity produced by boiling was within the range of experimental error. The fact that the turbidity of the raw deionized water did not remain constant with time is attributed to the aging and breakdown of the resin bed of the deionizer.

Triply distilled water from a Barnstead Still was also studied. Again the increase in the turbidity value caused by boiling could be attributed to experimental error. The triply distilled water had the lowest turbidity value found in any of the waters investigated. The turbidity of this water remained constant with a value of 6.0×10^{-5} $cm.^{-1}$ at 436 mμ, and a value of 3.4×10^{-5} $cm.^{-1}$ at 546 mμ. This water was used for all dilutions in this study.

Turbidity Standards

The criteria for a standard are, a turbid stock suspension which is easily prepared, has reproducible turbidities, and which can be diluted

to form turbid suspensions which will be stable for a period of at least two to three months. The stability depends on the material, the method of preparation of the suspension, and on the size of the suspended particle. In this study suspensions of several types of materials have been investigated including ionic compounds, various clays, polystyrene latexes, formazin, and Ludox.

Ionic compounds. Suspensions of several ionic compounds have been investigated on a short-term basis. All of these suspensions proved to be unsatisfactory.

Suspensions of calcium carbonate were investigated. These suspensions settle so rapidly that false values are obtained with Beckman's DU and DK-2 Spectrophotometers unless the suspension is shaken constantly. Table III shows the turbidity values obtained with a DU by shaking before

Table III

Turbidity Values of Calcium Carbonate Suspensions

λ in mμ	1[a], τ in cm.$^{-1}$	2[b], τ in cm.$^{-1}$	3[c], τ in cm.$^{-1}$
600	0.350	0.253	--
500	0.405	0.138	--
475	--	0.098	0.276
400	0.489	0.098	0.138
330	0.430	0.081	0.103

[a] Suspension shaken before each measurement, instrument DU.

[b] Suspension shaken before the 600 mμ measurement, instrument DK-2.

[c] Suspension shaken before the 475 mμ measurement, instrument DK-2.

each measurement, making an approximate reading, shaking again, and rapidly measuring the turbidity value. Table III also shows turbidity values obtained with the DK-2 with the suspension being shaken only before the first value was obtained. The DU values indicate that the turbidity value should increase with a decrease in wave length, but the settling is so rapid that the reverse is indicated by the DK-2 values, the scanning time was a few minutes, the shortest possible time.

Suspensions of barium sulfate were investigated. Table IV shows the effect of time on the turbidity of these suspensions. The rapid rate of change indicates that the particle size is changing and that the compound is not a suitable turbidity standard.

TABLE IV

Turbidity in $cm.^{-1}$ of Barium Sulfate Suspensions

Conc. in ppm	19.2	19.2	38.4	38.4	57.6	57.6
Wave Lengh in mμ	380	436	380	436	380	436
Age in Hours						
0	0.414	0.253	0.805	0.483	1.772	1.263
4	0.460	0.295	0.944	0.691	1.405	1.105

Suspensions of silver chloride were also investigated since much of the turbidity work in the past has been done using silver chloride suspensions. These suspensions were light sensitive and studies were carried out in semidarkness. Table V shows the effect of age on silver chloride suspensions. The effect of charge and of an excess common ion on the stability is also shown. The chloride ion apparently is a better stabilising excess common ion than the silver ion. Furthermore the most

stable suspension is formed when the ions are present in the ratio of one silver ion to two chloride ions. The requirement of semidarkness makes any silver halide suspension an undesirable standard regardless of the stability.

Turbidity in $cm.^{-1}$ at 345 mμ of Silver Chloride Suspensions

meq. Ag^+/100 ml.	28	28	14	70	14	140	14
meq. Cl^-/100 ml.	28	14	28	14	70	14	140
Age in Hours							
1/2	0.666	0.826	0.712	0.851	0.666	0.758	0.758
1	0.506	0.851	0.712	0.805	0.690	0.826	0.758
2	--	0.873	0.712	0.712	0.644	0.826	0.690
3	--	--	--	0.644	0.644	0.826	0.575
4	0.414	0.873	0.712	0.528	0.621	--	0.528
5	0.368	--	--	--	--	0.782	0.482
6	0.333	0.873	0.712	0.345	0.621	0.758	0.356

Various clays. Four representative type clays were studied in detail. The method of preparation of the clay suspension is the chief factor in the stability of the suspension. All methods of preparation lead to rapid settling except when the suspensions are prepared by the procedure recommended in Chapter III. Table VI shows four consecutive measurements of the turbidity of the representative clays when the suspension was not prepared by the recommended method. These data indicate settling which indicates that the particle size must be small, and that the particle size effects the stability of a suspension.

Consecutive Measurements of the Turbidity[a] in cm.$^{-1}$ of Clay Suspensions

Clay[b]	Kaolinite	Bentonite	Illite	Fullers Earth
Time in Minutes				
0	0.001580	0.000688	0.000781	0.001378
2	0.001472	0.000676	0.000700	0.001378
4	0.000925	0.000638	0.000635	0.001362
6	0.000802	0.000600	0.000635	0.001346

[a]All turbidity measurements were made at 436 mμ with the Brice-Phoenix Light Scattering Photometer.

[b]All suspensions contained an estimated 5 ppm of suspended clay.

Tables X-XIX give the stability data for the clays studied and the effect of stabilising agents. It is indicated by Tables X, XI, XII, XVI, and XVII that clays need some stabilising agent. The effectiveness of potassium ferrocyanide varies with the clay studied. Preliminary studies on the effectiveness of potassium ferrocyanide as a stabilising agent were made. It appeared that the best dosage for stabilising suspensions of fullers earth and bentonite was 2 ppm. Tables XIII, XIV, and XVII give the data obtained from a long-range study. The effectiveness of potassium ferrocyanide is limited to a period of less than 2 weeks. A dosage of 5 ppm seems to be the best dosage for suspensions of illite. Kaolinite suspensions do not seem to be stabilised by potassium ferrocyanide.

Sodium hydroxide appears to be a fair stabilising agent as the data in Tables XV and XIX indicate. The dosage used was the amount of

sodium hydroxide necessary to raise the equilibrium pH of the suspension above a value of 9.0. The effect of sodium hydroxide on kaolinite and illite suspensions was not investigated.

Michaels and Morelos (85) indicate that stable suspensions of kaolinite can be prepared by converting the so-called hydrogen form into the sodium form with sodium hydroxide. The suspension should have a pH above 8.5. The disadvantage of this suspension is that the hydrogen form is prepared by electrodialysis. Grim (86) indicates that electrodialysis leads to the decomposition of the clay lattice, and states that:

> Numerous investigators have indicated that the electrodialysis of certain of the clay minerals may cause their decomposition. Thus Kelly has shown that, as the cations are replaced by H^+, aluminum moves from octahedral positions to exchange positions, and Hofman and Giese have shown that, in general, unexchangeable cations are lost from within the lattice before all the exchangeable cations are replaced by H^+.

The hydrogen form of kaolinite was prepared by electrodialysis. Table VII shows the effect of varying the pH of the suspension. The

TABLE VII

Turbidity[a] in $cm.^{-1}$ of Suspensions of Hydrogen Form Kaolinite[b]

Equilibrium pH	Age in Days	
	One	Two
6.36	0.001472	0.001440
7.28	0.002100	0.001970
8.69	0.001940	0.001665
9.70	0.003410	0.002980

[a]All turbidity measurements were made at 436 mμ with a Brice-Phoenix Light Scattering Photometer.

[b]All suspensions contained an estimated 5 ppm of clay.

change in pH does not help the stability since all of the suspensions settled rapidly. All electrodialysis studies of clays were discontinued because of this lack of stability and because of the decomposition of the clay lattice reported by Grim.

The Hartman-Leddon Company produces a commercial turbidity standard of fullers earth. It was found to settle quite rapidly as Table VIII indicates. The turbidity values in this table were obtained on a Brice-Phoenix Light Scattering Photometer at 436 mμ. These turbidity values indicate that this standard is not a stable suspension.

TABLE VIII

Turbidity in $cm.^{-1}$ of the Harleco Fullers Earth Standard[a]

Time in Minutes	Turbidity	
	First Day	Ten Weeks Later
0	0.001252	0.000302
2	0.000792	0.000169
4	0.000690	0.000129
6	0.000566	--
8	0.000495	--
10	0.000485	--

[a]Concentration of fullers earth is 10 ppm.

Formazin. Formazin is an easily prepared, reproducible standard polymer. Its stability is limited and is a function of the time between shakings. For short periods of time this polymer makes a suitable standard. Tables XX-XXIII show turbidity with both concentrations of the polymer and time as variables. It is noted that up to a point the more

frequent the shakings the greater the stability. After six weeks time the interval between shakings does not affect the stability. The formazin polymer settles on standing and must be shaken vigorously to resuspend the polymer. The rate of settling is more rapid as the concentration increases, but the rate is too slow to be observed either with the human eye or with consecutive instrument readings. One of the good qualities of the formazin suspensions is that the turbidity values of the freshly prepared suspensions are fairly reproducible. The turbidity values for the fresh suspensions in Tables XX-XXIII agree very closely with an average deviation from the mean value of less than 2 per cent for the more concentrated suspensions. The decrease in the turbidity of the more dilute suspensions is more rapid than the decrease in the more concentrated suspensions.

Ludox. Ludox is a suspension of colloidal silica with a very small particle diameter. The stability of the Ludox suspensions is shown in Tables XXIV and XXV. From these results it appears that triply distilled water is a better stabilizing agent than 0.05 M NaCl. This is the reverse of what Goring, et al. (40) reported. The variation in the turbidity values of the 300 ppm and 30,000 ppm suspensions are so small that the variation in the turbidity values could be attributed to an error in the galvanometer reading. If the stability were the only property of a standard, Ludox would qualify. The big problem with this colloidal silica is that it must be present in a high concentration and in the concentrated form the suspensions attack soft glass, hands, and other items.

Polystyrene latex. The stability data for suspensions of the polystyrene latexes are shown in Tables XXVI-XXXIX. The most stable

suspensions of the polystyrene latexes appear to be the suspensions of polystyrene latex with particle diameters of 88 mμ, 188 mμ, 264 mμ, and 365 mμ. In some cases the variations in turbidity are so small that the error could be attributed to an error in the galvanometer reading. Another desirable factor about these polystyrene latexes is the fact that the concentration is known to 0.01 of 1 per cent with an accuracy of 1 part per thousand. These suspensions are very easy to handle and a small weight of polystyrene latex produces a suspension exhibiting high turbidity values.

The 88 mμ diameter polystyrene latex forms very stable suspensions as Tables XXVI and XXVII indicate. Most of the turbidities of the suspensions varied less than 2 per cent in the 12-week period, and the variation can be attributed to experimental error. The 0.58 ppm suspension had visible threadlike particles in it and apparently was contaminated at some time when the bottle was opened for a measurement. The value of 1.5×10^{-4} cm.$^{-1}$ for the fourth week for the 0.29 ppm suspension was apparently in error. The concentration of the 88 mμ diameter polystyrene latex suspensions is larger because of the small particle diameter. As the size of the particle increases the sensitivity per milligram of suspended matter increases until the diameter of the particles and the wave length of the light used in the measurement are the same value.

The 188 mμ diameter polystyrene latex forms stable suspensions as indicated in Tables XXVIII and XXIX. The turbidity values vary slightly more than the 88 mμ diameter suspensions. No explanation can be given for the suspensions of 0.28 and 0.14 ppm.

The 264 mμ diameter polystyrene latex forms stable suspensions as indicated by Tables XXX and XXXI. The particle size has increased and the time that the suspensions are stable has been shortened. At the end of 6 weeks the values have remained fairly constant and the variation is about 2 per cent except for the extremely dilute suspensions. By 8 weeks the lack of stability is indicated, and the 10-week data confirmed this lack of stability. Something unexplainable is occurring in the 1.08 and 0.54 ppm suspensions. Apparently the 0.054 and the 0.033 ppm suspensions are so dilute that the amount of polymer stabilizer present in the initial stock has been diluted beyond the limits of usefulness. The value of 3.8×10^{-4} cm.$^{-1}$ for the second week of the 0.27 ppm suspension appears to be in error.

The 365 mμ diameter polystyrene latex also forms stable suspensions as indicated by Tables XXXII and XXXIII. Again the increase in particle diameter has shortened the time that the turbidity value of the suspension remains relatively constant. At the end of 6 weeks the suspensions appear to be stable and the fluctuations in the turbidity values can be experimental errors. At the 8-week measurement the fluctuations in the turbidity values have increased to 4 per cent in some cases and in others it is as high as 8 per cent. This large increase does not necessarily indicate a poorer stability reading because the error inherent in the galvanometer is not linear with the size of the deflection and the relative error is also not linear with the size of the deflection. One interesting fact is that as some of the 365 mμ diameter polystyrene latex suspensions become unstable an increase in the turbidity value is noted rather than a decrease. This is especially noticed in the more dilute suspensions, i. e., the 0.05, 0.10, and the 0.03 ppm suspensions.

The 557 mμ diameter polystyrene latex suspensions are not as stable as the suspensions of the smaller diameter polystyrene latexes as shown by Tables XXXIV and XXXV. The limit of the stability with any suspension of the 557 mμ diameter polystyrene latex is apparently between 4 and 6 weeks.

Tables XXXVI and XXXVII indicate that the 814 mμ diameter polystyrene latex suspensions are not as stable as the suspensions of the smaller diameter polystyrene latex particles. The 4.32 and 3.83 ppm suspensions appear to be the most stable. Apparently the combination of a small enough number of particles and an adequate amount of stabiliser keeps the particles in suspension. The 1.72 ppm suspensions appears to be stable for six weeks. In the remaining suspensions it appears that if the shaking is adequate to resuspend all of the particles then the turbidity value is up; if the shaking is inadequate then the turbidity value is low.

Tables XXXVIII and XXXIX show that the 1171 mμ diameter polystyrene latex particles are too big to form stable suspensions. The 2.95 ppm suspension is the only suspension which approaches being stable. The other suspensions are in such a state that the turbidity value is determined by the effectiveness of the resuspension of the particles just prior to the measurement of the turbidity.

This study indicated that for long range stability either the 88 mμ diameter polystyrene latex suspensions or the 188 mμ diameter polystyrene latex suspensions are best suited as standards. As the particle size of the polystyrene latex increases the length of time that the suspension is stable decreases. The 188 mμ diameter polystyrene latex suspensions actually have several advantages. First, the diameter is

approximately one-half of 436 mμ and maximum sensitivity can be obtained by using this wave length, particle diameter ratio. Second, the concentration of the 186 mμ diameter polystyrene latex suspension can be lower than that of the 88 mμ diameter polystyrene latex suspension and still produce the same turbidity value. The 88 mμ diameter polystyrene latex suspensions have the advantage that many of the particles suspended in natural waters are very small, since the diameter of the standard and of the unknown should be as near the same size as possible in order to obtain optimum results.

Turbidity Measurements

Turbidity is an optical effect and one encounters many factors of optical importance when deciding how to measure the turbidity of a suspension. The first factor is the wave length of light to be used in the measurement. The second factor is the instrument to be used in the measurement. The third factor of importance is how does the turbidity value vary with a change in concentration once an instrument and a particular wave length have been chosen for the measurement.

Choice of wave length. The wave length of light to be used in the measurement of turbidity is limited by several factors. First, the wave lengths of light which are available to be used in the measurement of turbidity. Turbidity is usually measured in the visible region of the electromagnetic spectrum. This includes the region from 700 mμ to 350 mμ. In some cases the instrument is not sensitive over the entire region. Also when the monochromator is a filter the choice of wave length is even more limited.

Second, the value of the turbidity of a given suspension varies with the wave length of light used in the measurement. The optimum wave length of light to be used in the measurement varies with the particle diameter. Figures 1 and 2 show how the turbidity varies with both particle size and with wave length. If these figures extended from 3 microns to 1 mμ the trend of all 11 suspensions could be observed. As the particle diameter decreases the size of the plateau decreases. The plateau begins when the wave length is about one-half the diameter and continues for varying distances. The desirable region for making measurements is on the plateau. Since this is not possible in all cases a region of optimum sensitivity is the desired wave length to use for making turbidity measurements. When the wave length is in the region between twice the value of the particle diameter and the value of the particle diameter this appears to be an optimum region for the 365 mμ, 264 mμ, and 188 mμ diameter particles. The optimum available sensitivity for the 88 mμ diameter particles is a wave length nearly four times the diameter. The suspensions of Ludox with a diameter of 7 mμ would have to be measured in the ultra violet region of the electromagnetic spectrum in order to obtain maximum sensitivity. In Figure 1 all of the polystyrene latex suspensions were of approximately equal concentrations so that the variations due to concentration differences would be at a minimum.

In considering the instrumental limitations and also the factor of particle size all measurements were made in the region of 435 mμ or 436 mμ in this study of turbidity measurements. After considering all of the factors this wave length appeared to be the best one to use.

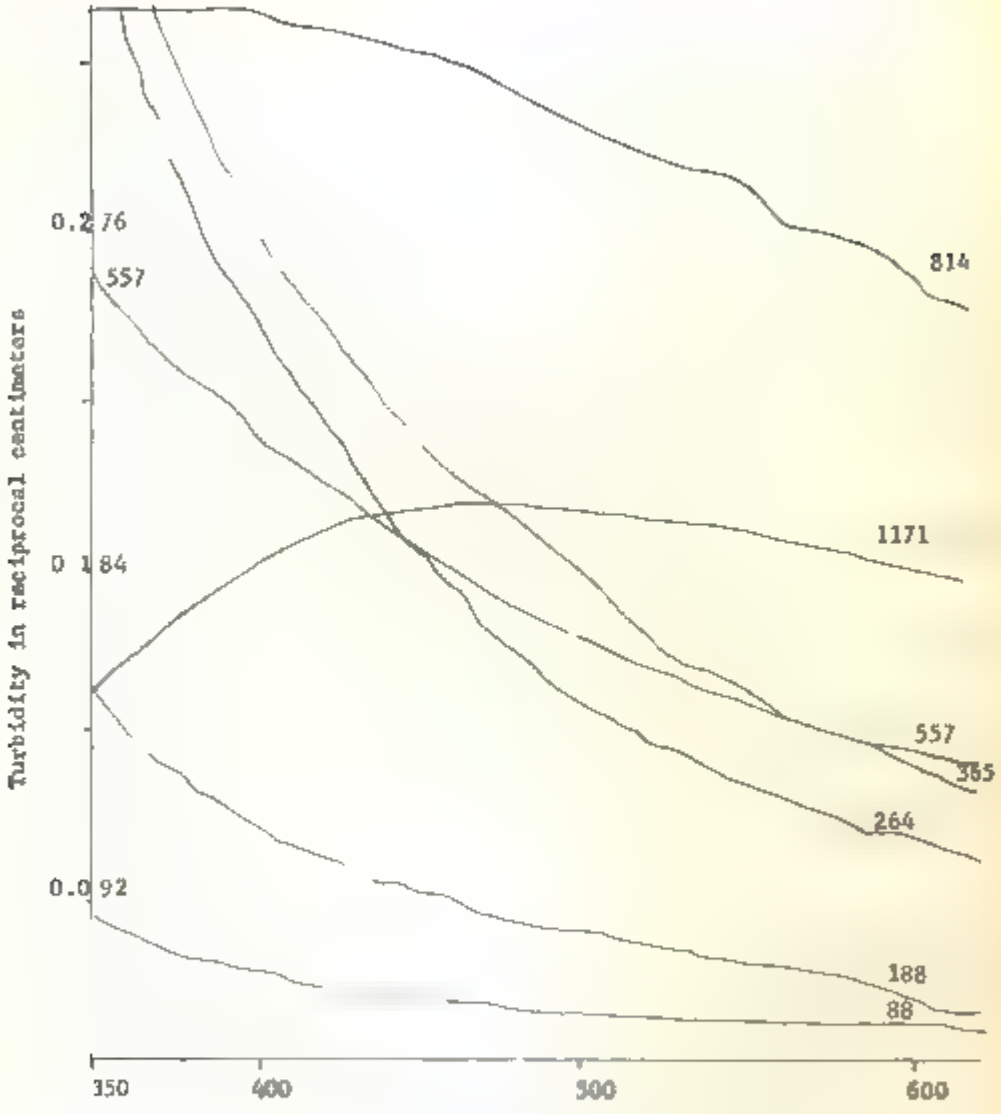

Fig 1—Turbidity Spectra of Polystyrene Latex Suspensions

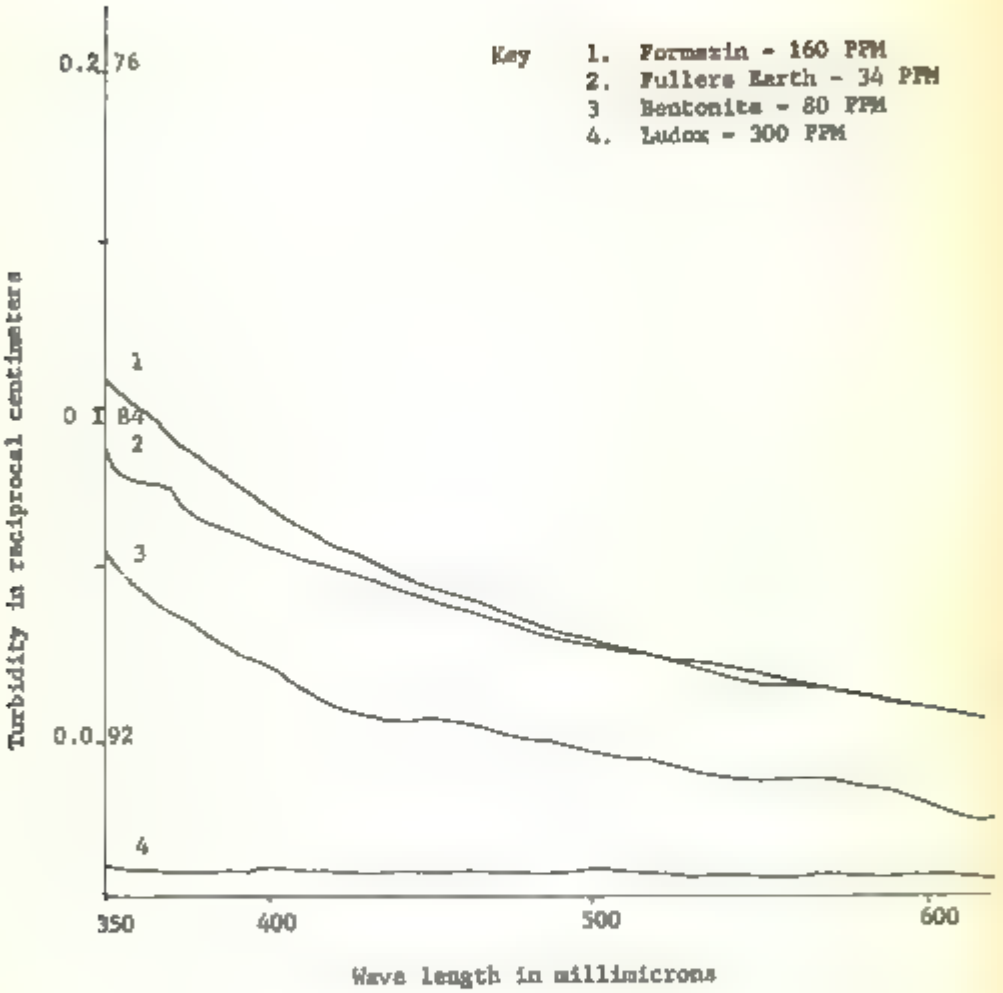

Fig. 2—Turbidity Spectra of Assorted Suspensions

Some of the Beckman DU readings were also made at 375 mμ in order to obtain greater sensitivity.

Choice of instrument. Turbidity can be measured by BOTH light scattering and light transmission methods. There are instruments which are based on both of the above principles. Both types of instruments are equipped with either photoelectric detectors or use the human eye as the detector. There are also some diaphanometers in use which employ the extinction principle. In this discussion the diaphanometer will be considered as an instrument based on light transmission. The reason for this is that instead of the amount of light which is transmitted being the variable the cell path is the variable and the amount of light transmitted is a constant.

In this study nine suspensions were used to compare nine different instruments which can be used to determine the turbidity. The results of this comparison are shown in Table IX. Eight of these suspensions have an approximate weight concentration of 3 ppm. This concentration was selected because it would be sensitive to both light scattering and light transmission methods. Suspensions of polystyrene latex are sensitive to both types of measurements at this concentration. It was decided to use suspensions of approximate concentrations in order to eliminate the factor of differences due to concentration. The formazin suspension requires a higher concentration for any sensitivity. The choice of instruments was limited to the instruments which were available.

The only visual transmission instrument which was used in this study was the Jackson Candle Turbidimeter. This instrument cannot be used for very dilute suspensions. It is a diaphanometer which was the most modern instrument available when it was designed in 1900. The

TABLE IX

Comparison of Instruments

Material			Polystyrene Latex 68	Polystyrene Latex 185	Polystyrene Latex 164	Polystyrene Latex 365	Polystyrene Latex 357	Polystyrene 814	Polystyrene 1171	Formazin	Fuller's Earth
Conc. in ppm			2.90	3.68	3.78	3.89	3.02	3.83	3.94	160.0	5.4
Instrument	Wave Length in mμ	Cell Path in cm.									
Beckman DU[a]	436	0.997	0.019	0.044	0.185	0.185	0.085	0.123	0.067	0.048	0.005
Beckman B[a]	435	5.001	0.023	0.046	0.137	0.146	0.113	0.133	0.078	0.048	0.012
Beckman DB-G[a]	435	0.997	0.014	0.048	0.154	0.184	0.147	0.188	0.149	0.101	0.005
Spectronic 20[b]	435	1.27	0.018	0.054	0.133	0.130	0.107	0.151	0.083	0.053	0.005
Lumetron 430[b]	430	15.0	0.015	0.037	0.104	0.104	0.076	0.110	0.064	0.046	0.005
Brice-Phoenix[b]	436	5.00	0.014	0.038	0.068	0.049	0.018	0.052	0.013	0.018	0.001
Jackson Candle[c]	360	var	0.84	0.51	4.70	3.00	14.00	40.00	25.00	10.70	1.25
St Louis[d]	e	15	0.004	0.038	0.110	0.298	0.298	1.00	.443	—	0.118
Hellige[f]	e	1.0	[illegible]	156	156	158	130	760	180	—	63

[a]Turbidity in $cm.^{-1}$ transmission instrument.

[b]Turbidity in $cm.^{-1}$ light scattering instrument.

[c]Turbidity from the scale on the tube all values below 25 are extrapolated from more concentrated suspensions.

[d]Turbidity in $cm.^{-1}$ values obtained by using 400 mμ polystyrene latex suspensions as the standard.

[e]Energy source was an ordinary electric light bulb and no monochrometer was available

[f]Turbidity in ppm SiO_2 from the calibration chart furnished with the instrument.

Jackson Candle Turbidimeter uses a candle of beeswax and spermaceti as a source of light and the flame has a wave length of approximately 560 mμ. The scale for turbidities is etched on the tube. Extrapolated values are shown in Table IX. A steady increase in turbidity is observed with an increase in the particle diameter until the diameter is 814 mμ. This indicates again that the turbidity of a suspension is sensitive to particle size, because the concentrations by weight are approximately equal in these suspensions.

Any commercial filter photometer, photoelectric colorimeter, or spectrophotometer can be used as an instrument to measure turbidity. The desirable properties are a long cell path for dilute turbid suspensions, a sensitive detector, and an accurate monochromator. Instruments used in this study include a Beckmann DU, DK-2, and B Spectrophotometer, a Photovolt Lumetron 450, and a Bausch and Lomb Spectronic 20. The DU was operated at a wave length of 436 mμ. The Lumetron was operated using a 420 mμ blue filter as the monochromator. The wave length used for making the turbidity measurements was 435 mμ with the DK-2, B, and Spectronic 20. In Table IX all values for the above instruments were obtained as absorbancy. The turbidity was calculated using equation (1-2). The variation in turbidity value for the same suspension can be attributed to several factors. First, the instruments are of varying accuracy. Second, the same cell path was not used in all of the instruments. The agreement of the Spectronic 20 values with the other values is excellent considering the short cell path and the small size of the absorbancy. Third, one would expect some variation with the Lumetron values since the wave length of light used

in the measurement was not the same as the other transmission instruments. Fourth, the DK-2 is not set to give absolute absorbancy values. Whenever values of absorbancy from the DK-2 and the DU are compared the DU values are lower. This is attributed to the fact that the DU is the more absolute instrument of the two.

The only light scattering instrument with a photoelectric detector used in this study was the Brice-Phoenix Light Scattering Photometer. This instrument is equipped with a mercury lamp, filters, and a photomultiplier tube. The 436 mμ mercury line was used exclusively in this study. This instrument was used for obtaining all of the stability data. The values for the turbidity are given in $cm.^{-1}$ and are calculated by using equation (2-13). Table IX also shows turbidity values for the suspensions as obtained by light scattering techniques. Some of the values are much lower than the values obtained by transmission instruments. This difference is partly due to the dissymmetry of the scattering and the depolarization of the 90 degree scattering which are observed in light scattering.

The St. Louis Turbidimeter was the light scattering instrument with the human eye as the detector which was used in this study. Values are obtained by matching the unknown suspension with the standard suspension. This instrument is limited to determining the turbidity of suspensions with turbidities equivalent to the turbidity in clay suspensions which contain from 10.0 ppm to 0.1 ppm of clay. A further limitation is that the particles must be of similar sizes or aberrations due to the color of the scattered light result. The fact that the instrument does not employ a monochromator limits its use even more. Table IX shows the data

obtained on the St. Louis Turbidimeter for the 3 ppm polystyrene latex suspensions. The values are obtained by matching with 188 mμ diameter polystyrene latex suspensions. These values were then converted into $cm.^{-1}$ by the relation that 1 ppm of 188 mμ diameter polystyrene latex is equivalent to 0.01425 $cm.^{-1}$ at 436 mμ.

The Hellige Turbidimeter is a cross-bread instrument in that it employs both the transmission and scattering of light by the sample. This instrument does not use a monochromator with the standard light bulb which serves as the source of energy. Table IX shows the data obtained on this instrument. The values are in ppm of silica and cannot be correlated with the turbidities in $cm.^{-1}$.

Turbidity may be measured by either light absorption or by light scattering. The use of light absorption or light transmission is recommended until an absorbancy value or 0.025 or 95 per cent transmission is reached. For solutions with less turbidity, light scattering techniques are necessary. The Brice-Phoenix Light Scattering Photometer can detect turbidity in the purest distilled water available.

Variation of turbidity with concentration. It is known that an increase in concentration will produce an increase in turbidity at a specific wave length. The problem is not the general trend, but does the turbidity vary linearly with concentration, does the logarithm of the turbidity vary linearly with the logarithm of concentration, or is the functional relationship even more complex.

Looking again at the instruments used in Table IX, the turbidity values fall into four groups. The first and largest group is the photoelectric transmission instruments containing, Beckman DU, B, and

DK-2 Spectrophotometers, a Bausch and Lomb Spectronic 20, and a Photovolt Corp. Lumetron 450. The second group consists of one instrument, a Jackson Candle Turbidimeter. The third group consists of only one instrument, the Brice-Phoenix Light Scattering Photometer. The fourth group contains two instruments, the St. Louis and Hellige Turbidimeters.

Turbidity varies linearly with concentration when the turbidity is measured with a transmission instrument. Figure 3 shows the variation of turbidity with concentration for various sized suspended particles. These values were obtained with a DU at 436 mμ using 10-cm. absorption cells. The slope of the line is dependent on three factors, the size of the suspended particle, the wave length used in making the measurement, and the instrument used in making the measurement. From Figure 1 one would expect that the slope of the lines would vary with the particle size. The relative positioning of the lines also varies with the wave of light used in making the measurement. This fact is also predicted from Figure 1. The variation of turbidity with a change in concentration for the varying sized particles at 546 mμ is shown in Figure 4. These turbidity values were obtained by using the DK-2. This figure closely resembles the figure and work reported by Tabibian, Heller, and Spel (54). The equation describing the variation of turbidity with concentration for a given instrument is $\tau = m\,c$, where m is the slope of the line and is a function of the particle size and of the wave length of light used in making the measurement. As concentration increases a negative deviation from linearity is noticed. The careful choice of the cell path can minimize this deviation.

The turbidity does not vary linearly with the concentration when the Jackson Candle Turbidimeter is used to determine turbidity. The

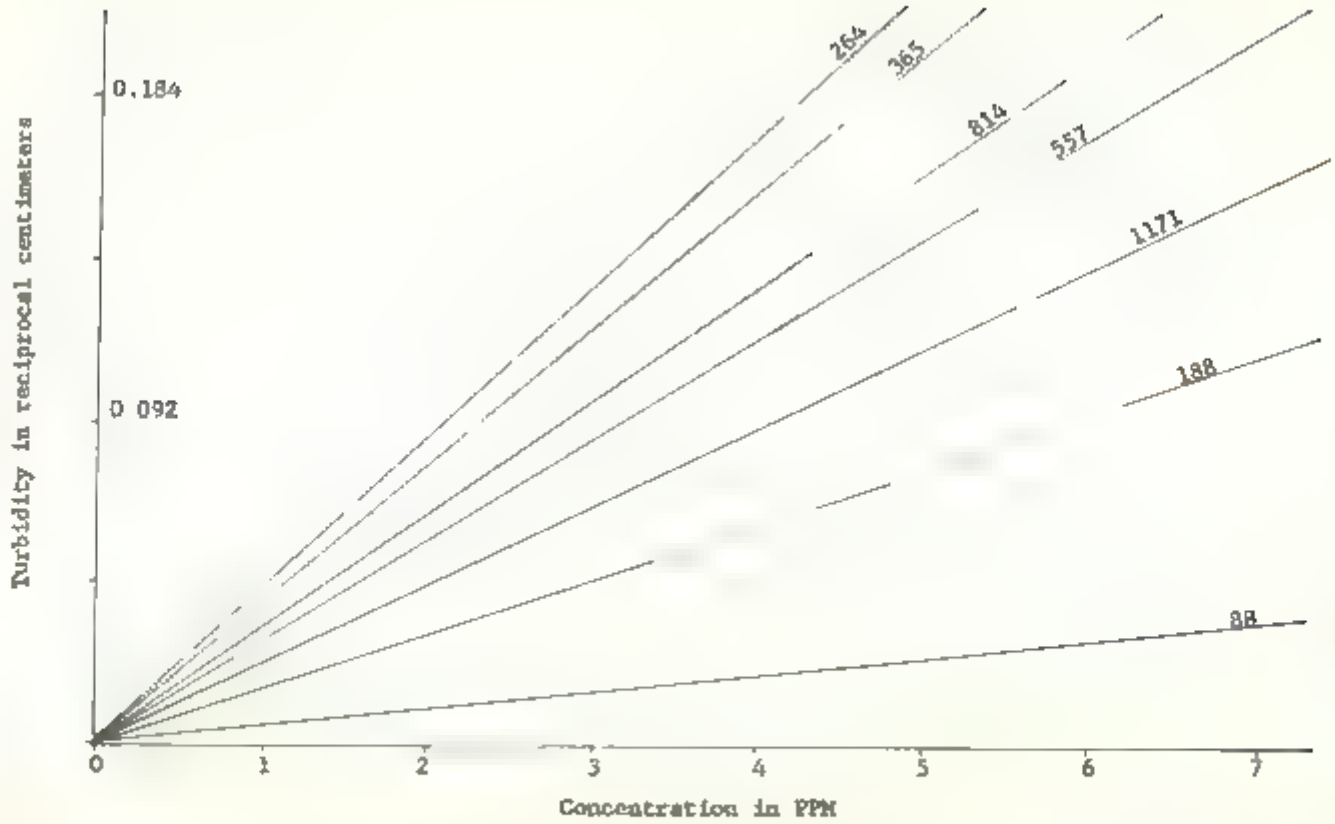

Fig. 3—Effect of Particle Size and Concentration on Turbidity[1]

1. Instrument Beckman DU, Wave Length 436 mμ

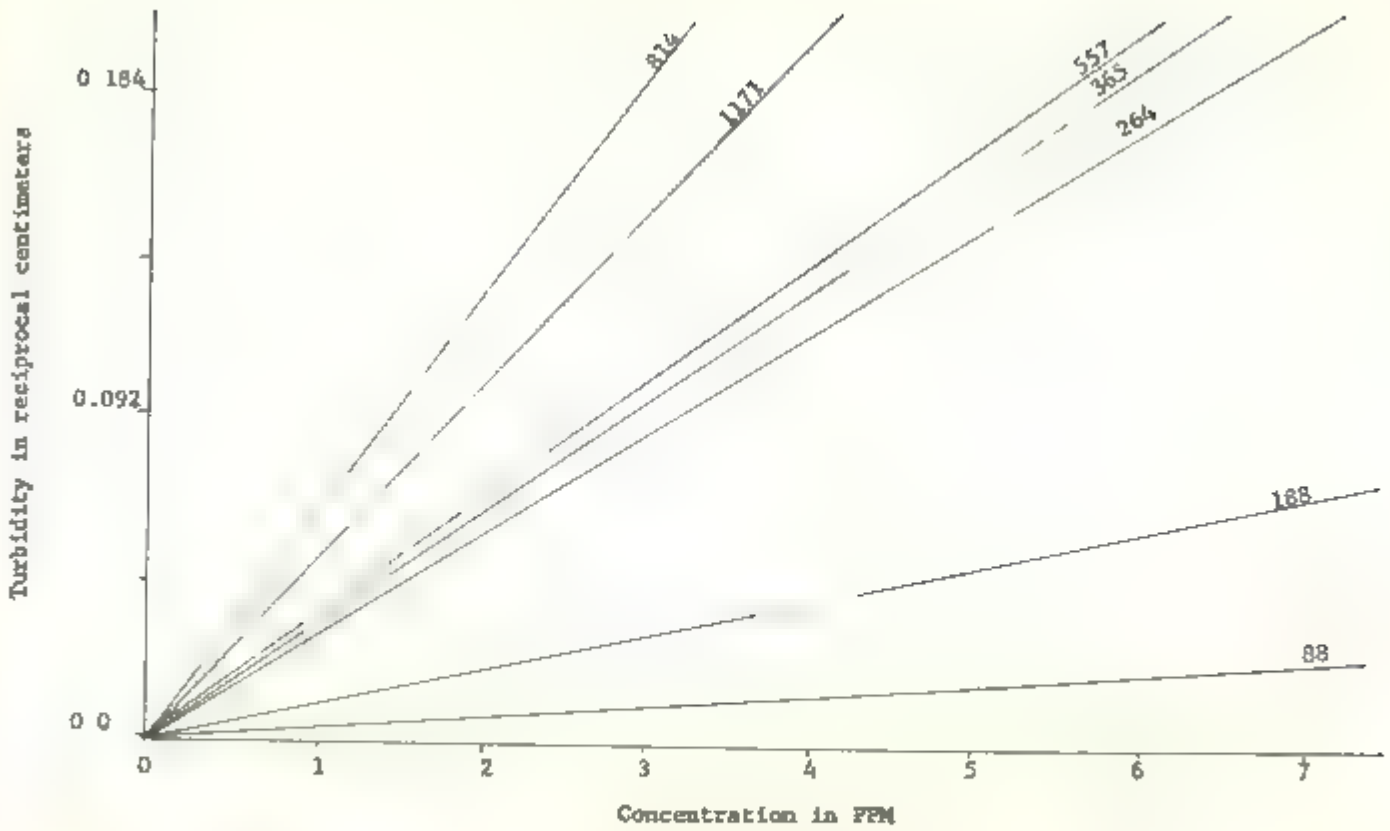

Fig. 4—Effect of Particle Size and Concentration on Turbidity[1]

1. Instrument Beckman DK-2, Wave Length 546 mμ

depth of the liquid in the tube does vary linearly with concentration. The logarithm of the turbidity varies linearly with the logarithm of the concentration. This linear relationship is shown in Figure 5. The data in Figure 5 are for suspensions of polystyrene latexes of 88 mμ, 188 mμ, 365 mμ, and 814 mμ particles. Other sized particles produce straight lines with different slopes. An equation to describe this relationship is $\log \tau = a \log c + b$, where a and b are constants which depend on the size of the suspended particle.

When turbidity is measured with the Brice-Phoenix Light Scattering Photometer the plot of turbidity versus concentration varies in shape as the size of the particle. Figure 6 shows the various shaped curves. The general trend is an increase in turbidity with an increase in concentration. Particles with 88 mμ and 188 mμ diameters produce turbidities which vary linearly with concentration. Light scattering techniques are very sensitive to the various sized particles. When the particle size approaches the wave length of light used in the measurement dissymmetry, depolarization, and secondary scattering effects alter the turbidity. With the 1171 mμ, 557 mμ and the 814 mμ suspensions reflection effects may also affect the results. When the suspended particle is larger than the wave length reflection occurs (87). When the logarithm of turbidity is plotted against the logarithm of concentration the only suspensions which depart from linearity are the 365 mμ and the 264 mμ suspensions. Straight lines can be obtained by plotting $\log 1/c\tau$ versus $\log c$ or Hc/τ versus c, but this has no analytical significance for the determination of unknown concentrations from turbidities. In the lower regions of concentrations all of the suspensions approach linearity.

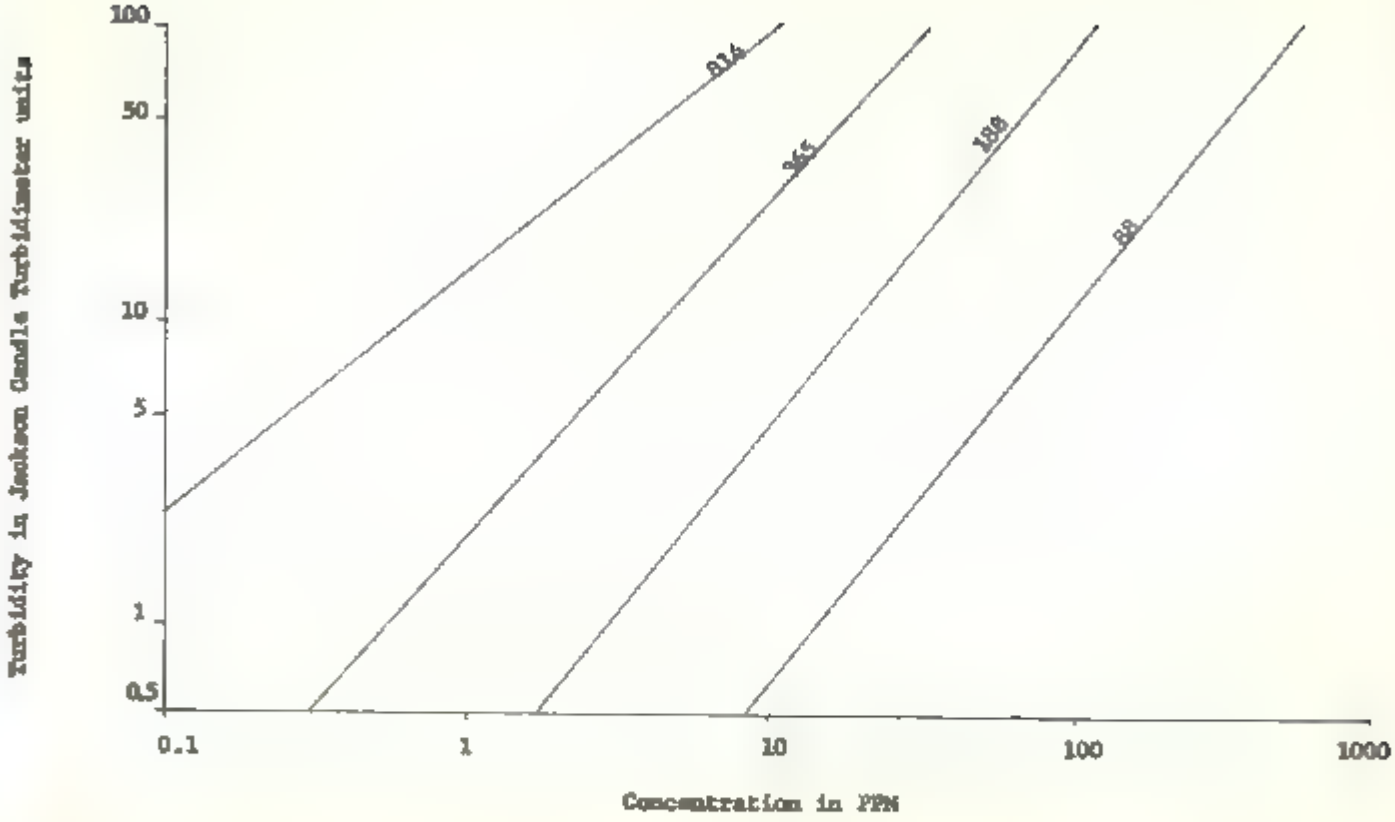

Fig. 5—Effect of Particle Size and Concentration on Turbidity

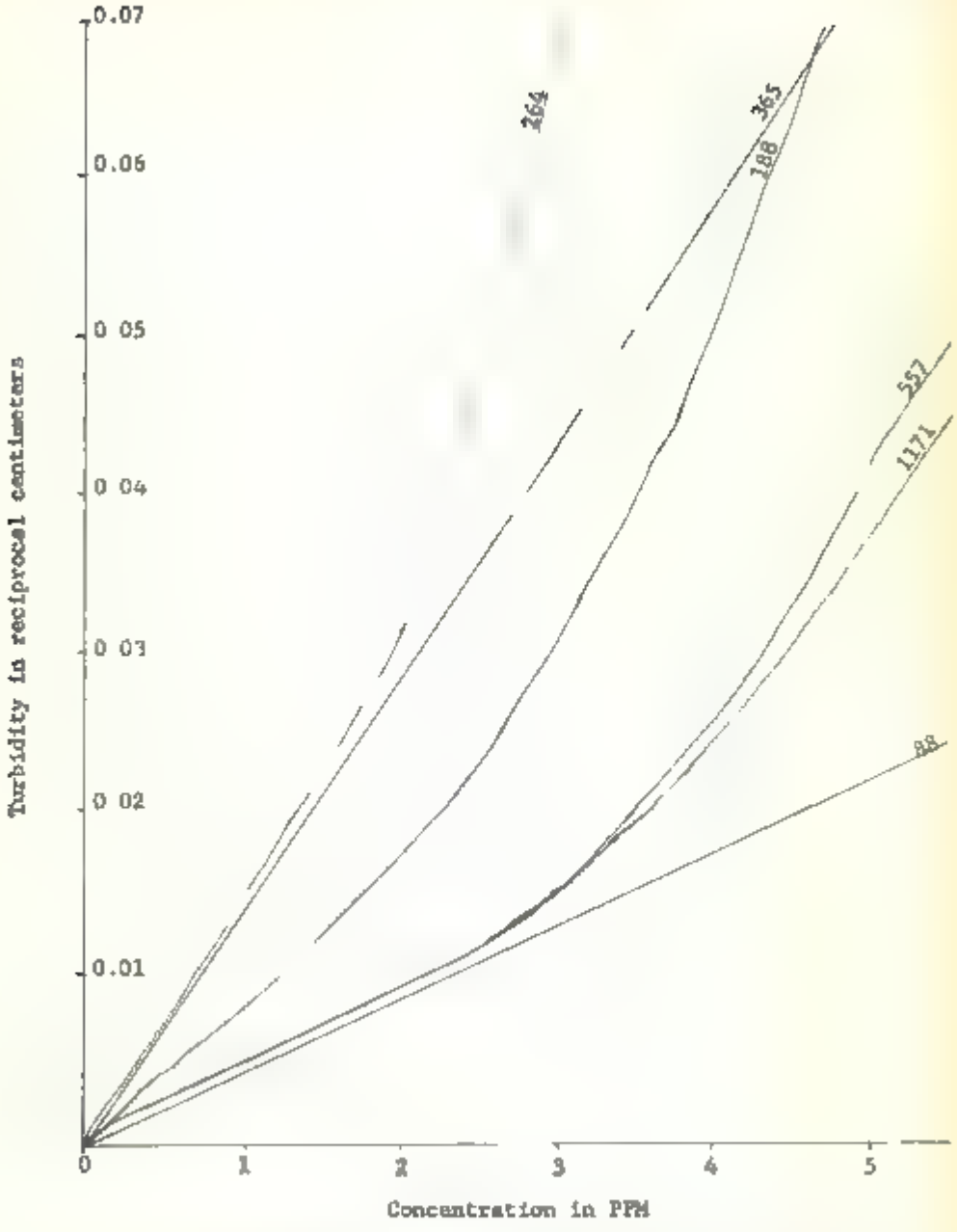

Fig. 6—Effect of Particle Size and Concentration on Turbidity[1]

1 Instrument Brice-Phoenix, Wave Length 436 mμ

In order to calculate H it was necessary to obtain the difference in the refractive indices of the suspensions and the solvent. Table XI. shows the data obtained by using a Brice-Phoenix Differential Refractometer with the mercury blue line at 436 mμ.

Time did not permit an investigation of the variation of turbidity with concentration in the St. Louis Turbidimeter or with the Hellige Turbidimeter. It is expected that the St. Louis turbidity values vary linearly with concentration.

Once a standard and unknown of approximately the same particle size have been chosen, then the instrument for determining the turbidity must be chosen. After the standard, instrument, and concentration range for the turbidity have been chosen then the measurement of concentration from turbidity is simply a matter of making a standard curve, reading the unknown, finding the turbidity value on the curve and reading the concentration from the curve.

[redacted]

The following values are very useful for conversions. One ppm of 188 mμ diameter polystyrene latex is equivalent to 0.01425 cm.$^{-1}$ at 436 mμ. One ppm of 88 mμ diameter polystyrene latex is equivalent to 0.00500 cm.$^{-1}$ at 436 mμ. One ppm of very fine centrifuged fullers earth is equivalent to 0.000281 cm.$^{-1}$ at 436 mμ. These values may also be related back to the Jackson Candle Turbidimeter units. One ppm of 188 mμ diameter polystyrene latex is equivalent to 0.17 Jackson Candle Turbidimeter units. One ppm of 88 mμ diameter polystyrene latex is equivalent to 0.03 Jackson Candle Turbidimeter units.

[redacted]

In this study suspensions of several materials have been investigated including various clays, several ionic compounds, seven polystyrene latexes, formazin, and Ludox. The stability of the suspension depends on the material, on the method of preparation of the suspension, and on the size of the suspended particle.

Before the investigation of a standard could begin, a turbidity free water was obtained. The water used in all dilutions was triply distilled water with a turbidity value of 6×10^{-5} cm.$^{-1}$ at 436 mμ.

Suspensions of ionic compounds studied were suspensions of calcium carbonate, suspensions of barium sulfate, and suspensions of silver chloride. All of these suspensions proved to be so unstable that no long-range study was pursued.

The clay suspensions investigated included suspensions of bentonite, fullers earth, illite, and kaolinite. These clay suspensions need some stabilizing agent. In this study potassium ferrocyanide and sodium hydroxide were investigated. Potassium ferrocyanide was not a good stabilizing agent for long periods of time. Sodium hydroxide was better as a stabilizing agent than the potassium ferrocyanide, but it left much to be desired. In order to obtain even a metastable clay suspension the procedure recommended in Chapter III must be followed.

Formazin is the standard suspension which is used by the Society of Brewing Chemists for the determination of turbidity. The suspension is

prepared by adding equal volumes of 1 per cent hydrazine sulfate solution and 10 per cent hexamethylenetetramine solution. The mixture is stirred constantly to increase the rate of polymerization. This stock suspension is diluted with turbidity free water. The stability of the suspension is dependent on the interval of time between shakings. This polymer makes a good standard for short periods of time.

Concentrated stock suspensions of polystyrene latex were supplied by the Dow Chemical Company. Suspensions of these polystyrene latexes were prepared by diluting a weighed quantity of the stock suspension. More dilute suspensions were obtained by further dilution. The polystyrene latex suspensions do not settle on standing. With the small diameter latexes the variations in the stability was within the range of experimental error. In addition to the stability these suspensions have another very desirable recommendation as a standard, i. e., the suspensions are easy to prepare and are easy to handle. Each stock suspension is of a known particle size, and the concentration is certified to 0.01 of 1 per cent with an accuracy of 1 part per thousand. Suspensions of polystyrene latex used in this study had particle diameters of 88 mμ, 188 mμ, 264 mμ, 365 mμ, 557 mμ, 814 mμ, and 1171 mμ.

Concentrated suspensions of Ludox were supplied by E. I. du Pont de Nemours and Company, Inc. Ludox is a colloidal silica with a particle diameter of 7 mμ to 15 mμ. Suspensions were prepared by dilution of the concentrated stock with turbidity free water. The stabilizing action of 0.05 M sodium chloride was studied. Sodium chloride in the concentration studied was not a stabilizing agent for Ludox. The suspensions in turbidity free water were quite stable. Ludox is not as desirable a

standard as the polystyrene latexes. First, the particle diameter is much less than the wave length of visible light or even ultra violet light. Since the diameter is so much smaller than the wave length of the light used in the measurement of the turbidity, the concentration of the particles must be large. Second, with the large concentration of particles the suspensions become difficult to handle.

The conclusions reached concerning a standard are as follows:

(1) The polystyrene latexes provide stable suspensions to be used as standards. For long range stability the 38 mμ or the 188 mμ particle diameter suspensions provide the most stable suspensions.

(2) The 188 mμ diameter particles have the advantage of being approximately the same value as one-half of the wave length of light used in the measurement.

(3) The diameter of the polystyrene latex to be chosen will depend on the relative diameter of the particles making up the unknown turbid suspension for the most accurate results.

(4) As an alternate standard, the formazin polymer may be used.

(5) The Ludoxes provide very stable suspensions, but lack other desirable properties necessary to make a good standard.

(6) Clay suspensions and suspensions of ionic compounds are not stable enough to be recommended as turbidity standards.

In this study both light transmission and light scattering instruments were used. The light transmission methods are simpler and are recommended for suspensions having an absorbance value greater than

0.025. For the more dilute suspensions light scattering methods are necessary. The turbidity of the suspensions may be calculated in $cm.^{-1}$ from both types of measurements.

The wave length of light used in making the measurement is also an important factor to consider in choosing the method of measurement. Optimum sensitivity is obtained when the particle size is between one-half of the wave length and the same size as the wave length of the light used in the measurement. In this study the visible region of the electromagnetic spectrum was scanned using a Beckman DK-2 Ratio Recording Spectrophotometer. For small particles the general rule is the smaller the wave length the greater the sensitivity. In this study the wave length used in measuring the turbidity of suspensions was 436 mμ if this wave length was available on the particular instrument being used.

A comparison study was made to see the variation in turbidity with a change in instrument. When the turbidity values were calculated in $cm.^{-1}$ the variations could be attributed to the variations in the quality of the instruments, the individual characteristics of the instruments, and the principles of operation of the individual instruments. The following instruments were used in this comparison study, a Beckman DU Spectrophotometer, a Beckman B Spectrophotometer, a Beckman DK-2 Spectrophotometer, a Bausch and Lomb Spectronic 20, a Photovolt Corp. Lumetron Modal 400, a Phoenix Precision Company Brice-Phoenix Light Scattering Photometer, a Jackson Candle Turbidimeter, a Phipps and Bird St. Louis Turbidimeter, and a Hellige Turbidimeter.

A Brice-Phoenix Light Scattering Photometer was used in this study to obtain the light scattering measurements. A Beckman DU Quartz

Spectrophotometer was used to make the transmission measurements in this study.

The conclusions reached concerning the method of turbidity measurement are as follows:

(1) Light transmission methods are simpler than light scattering techniques and should be used to measure the turbidity of all suspensions having an absorbence value greater than 0.025. For more dilute suspensions light scattering methods are necessary.

(2) The unit of turbidity measurement is the reciprocal centimeter. This value can be obtained from both light transmission and light scattering measurements.

(3) The use of photoelectric detectors in the measurement of turbidity is recommended.

(4) The wave length of light used in the measurement should be the wave length of light at which the greatest sensitivity is obtained.

(5) The region of optimum sensitivity depends on the particle size of the suspended material.

(6) In any turbidity measurement the standard and the unknown should be of approximately the same particle size.

(7) The turbidity of a suspension is a function of three factors, the weight concentration of suspended material, the size of the suspended particle, and the wave length of light used in the measurement.

(8) When other factors are held constant, the turbidity of a suspension varies linearly with the weight concentration in specific concentration ranges.

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APPENDIX

TABLE X

Turbidity[a] in cm.$^{-1}$ of Illite and Kaolinite Suspensions

Conc. of Illite in ppm	1.7	1.7	1.7	0.0	0.0	0.0
Conc. of Kaolinite in ppm	0.0	0.0	0.0	1.7	1.7	1.7
Conc. of $K_4Fe(CN)_6$ in ppm	0.0	5.0	10.0	0.0	5.0	10.0
Age in Weeks						
0	0.000340	0.000535	0.000480	0.001730	0.001760	0.001730
1	0.000109	0.000499	0.000456	0.000986	0.001542	0.001500
2	0.000091	0.000482	0.000489	0.000477	0.001460	0.001190
4	0.000085	0.000332	0.000382	0.000395	0.000848	0.000600
6	0.000115	0.000233	0.000285	0.000426	0.000643	0.000468
8	0.000123	0.000227	0.000271	0.000305	0.000261	0.000273
10	0.000125	0.000217	0.000299	0.000299	0.000332	0.000346
12	0.000135	0.000167	0.000182	0.000238	0.000168	--

[a]Turbidity at 436 mμ.

TABLE XI

Turbidity[a] in $cm.^{-1}$ of Fullers Earth Suspensions

Conc. of Fullers Earth in ppm	7.1	3.6	1.4	0.71	0.36	0.14	0.07
Age in Weeks							
0	0.001825	0.000738	0.000332	0.000196	0.000085	0.000048	0.000034
1	0.001670	0.000515	0.000266	0.000191	0.000086	0.000067	0.000058
2	0.001795	0.000566	0.000235	0.000149	0.000075	0.000069	0.000069
4	0.001810	0.000690	0.000196	0.000188	0.000067	0.000078	0.000057
6	0.001970	0.000659	0.000173	0.000109	0.000092	0.000067	0.000054
8	0.002100	0.000695	0.000183	0.000126	0.000092	0.000061	0.000056
10	0.002370	0.000873	0.000281	0.000132	0.000125	0.000096	0.000071
12	0.002610	0.000873	0.000280	0.000128	0.000170	0.000080	0.000072

[a]Turbidity at 436 mμ.

TABLE XII

Turbidity[a] in $cm.^{-1}$ of Fullers Earth Suspensions

Conc. of Fullers Earth in ppm	17.00	7.00	3.40	1.70	0.70	0.34	0.17
Age in Weeks							
0	0.00548	0.00201	0.001000	0.000519	0.000225	0.000152	0.000045
2	0.00505	0.00171	0.000848	0.000480	0.000243	0.000162	0.000101
4	0.00426	0.00127	0.000734	0.000399	0.000238	0.000152	0.000100
6	0.00404	0.00125	0.000652	0.000502	0.000262	0.000125	0.000094
9	0.00425	0.00123	0.000970	--	0.000260	0.000137	0.000125

[a]Turbidity at 436 mμ.

TABLE XIII

Turbidity[a] in $cm.^{-1}$ of Stabilized[b] Fullers Earth Suspensions

Conc. of Fullers Earth in ppm	7.1	3.6	1.4	0.71	0.36	0.14	0.07
Age in Weeks							
0	0.001825	0.000738	0.000332	0.000196	0.000085	0.000048	0.000034
1	0.001910	0.000918	0.000430	0.000306	0.000212	0.000118	0.000116
2	0.001883	0.000912	0.000447	0.000290	0.000193	0.000157	0.000159
4	0.001810	0.001050	0.000525	0.000332	0.000223	0.000206	0.000214
6	0.002100	0.001090	0.000576	0.000320	0.000211	0.000260	0.000193
8	0.002290	0.001148	0.000645	0.000356	0.000272	0.000238	0.000221
10	0.002640	0.001305	0.000706	0.000412	0.000306	0.000266	0.000228
12	0.002920	0.001291	0.000712	0.000382	0.000287	0.000230	0.000197

[a]Turbidity at 436 mμ.

[b]Stabilizing agent was 2 ppm of $K_4Fe(CN)_6$.

TABLE XIV

Turbidity[a] in $cm.^{-1}$ of Stabilised[b] Fullers Earth Suspensions

Conc. of Fullers Earth in ppm	17.00	7.00	3.40	1.70	0.70	0.34	0.17
Age in Weeks							
0	0.00439	0.00212	0.00105	0.000600	0.000269	0.000169	0.000095
2	0.00356	0.00194	0.00098	0.000551	0.000292	0.000292	0.000653
5	0.00334	0.00190	0.00109	0.000590	0.000317	0.000420	0.000892
8	0.00287	0.00200	0.00126	0.000668	0.000370	0.000380	0.001090

[a]Turbidity at 436 mμ.

[b]Stabilising agent was 2 ppm of $K_4Fe(CN)_6$.

TABLE XV

Turbidity[a] in $cm.^{-1}$ of Stabilised[b] Fullers Earth Suspensions

Conc. of Fullers Earth in ppm	17.00	7.00	3.40	1.70	0.70	0.34	0.17
Age in Weeks							
0	0.00481	0.00201	0.00106	0.000572	0.000260	0.000145	0.000116
2	0.00480	0.00209	0.00103	0.000548	0.000238	0.000156	0.000103
5	0.00466	0.00205	0.00101	0.000546	0.000250	0.000190	0.000123
8	0.00469	0.00200	0.00099	0.000554	0.000251	0.000170	0.000112

[a]Turbidity at 436 mμ.

[b]Stabilising agent was NaOH.

TABLE XVI

Turbidity[a] in cm.$^{-1}$ of Volclay Montmorite Suspensions

Conc. of Volclay in ppm	8.0	4.0	2.0	1.0	0.8	0.4	0.2	0.1
Age in Weeks								
0	0.000600	0.000346	0.000368	0.000142	0.000157	0.000087	0.000092	0.000067
2	0.000662	0.000382	0.000615	0.000154	0.000135	0.000103	0.000105	0.000083
5	0.000700	0.000492	0.000884	0.000210	0.000168	0.000168	0.000131	0.000078
8	0.000668	0.000436	0.001020	0.000195	0.000144	0.000125	0.000135	0.000096

[a]Turbidity at 436 mμ.

TABLE XVII

Turbidity[a] in $cm.^{-1}$ of Volclay Bentonite Suspensions

Conc. of Volclay in ppm	7.70	7.70[b]	3.85	3.85[b]	1.54	1.54[b]	0.77	0.77[b]
Age in Weeks								
0	0.000834	0.000834	0.000467	0.000467	0.000228	0.000228	0.000151	0.000151
1	0.000898	0.000682	0.000495	0.000386	0.000231	0.000173	0.000133	0.000144
2	0.000820	0.000940	0.000462	0.000545	0.000227	0.000281	0.000169	0.000130
4	0.000985	0.000890	0.000583	0.000530	0.000292	0.000260	0.000144	0.000196
6	0.001002	0.000959	0.000794	0.000606	0.000352	0.000296	0.000166	0.000240
8	0.001035	0.000970	0.000649	0.000646	0.000298	0.000336	0.000193	0.000287
10	0.001110	0.001028	0.000688	0.000724	0.000332	0.000386	0.000233	0.000359
12	0.001090	0.001035	0.000674	0.000700	0.000320	0.000376	0.000212	0.000459

[a]Turbidity at 436 mμ.

[b]Indicates the presence of 2 ppm of $K_4Fe(CN)_6$.

TABLE XVIII

Turbidity[a] in $cm.^{-1}$ of Stabilised[b] Volclay Bentonite Suspensions

Conc. of Volclay in ppm	8.0	4.0	2.0	1.0	0.8	0.4	0.2	0.1
Age in Weeks								
0	0.000622	0.000372	0.000215	0.000175	0.000171	0.000152	0.000140	0.000109
2	0.000700	0.000406	0.000247	0.000234	0.000183	0.000154	0.000160	0.000158
5	0.000952	0.000662	0.000390	0.000468	0.000374	0.000446	0.000416	0.000382
8	0.001050	0.000666	0.000480	0.000492	0.000480	0.000422	0.000446	0.000446

[a]Turbidity at 436 mμ.

[b]Stabilising agent was 2 ppm of $K_4Fe(CN)_6$.

TABLE XIX

Turbidity[a] in cm.$^{-1}$ of Stabilised[b] Volclay Bentonite Suspensions

Conc. of Volclay in ppm	8.0	4.0	2.0	1.0	0.8	0.4	0.2	0.1
Age in Weeks								
0	0.000598	0.000334	0.000199	0.000145	0.000118	0.000121	0.000086	0.000077
2	0.000597	0.000337	0.000243	0.000147	0.000118	0.000110	0.000084	0.000080
5	0.000588	0.000317	0.000197	0.000144	0.000168	0.000103	0.000079	0.000094
8	0.000580	0.000352	0.000227	0.000158	0.000178	0.000118	0.000109	0.000115

[a]Turbidity at 436 mμ.

[b]Stabilizing agent was NaOH.

Turbidity[a] in cm.$^{-1}$ of Formazin Suspensions

Conc.[b]	1000	500	[illegible]	[illegible]	50	20	10
Conc.[c]	800	400	160	80	40	16	8
Age in Weeks							
0	0.1734	0.0576	0.0178	[illegible]	0.00370	0.00154	0.000757
1	0.1701	0.0565	0.0180	0.00819	0.00363	0.00148	0.000708
2	0.1692	0.0576	0.0176	0.00825	0.00355	0.00144	0.000667
3	0.1654	0.[illegible]	0.0176	0.00798	0.00347	0.00144	0.000664
4	0.1631	0.0548	0.0172	0.00790	0.00341	0.00147	0.000682
5	0.1654	0.0550	0.0170	0.00772	0.00334	0.00148	0.000673
6	0.1603	0.0536	0.0170	0.00751	0.00331	0.00142	0.000663
7	0.1610	0.0538	0.0170	0.00735	0.00340	0.00140	0.000675
8	0.1610	0.0531	0.0169	0.00730	0.00319	0.00139	0.000682
9	0.1621	0.0538	0.0167	0.00736	0.00323	0.00137	0.000682
10	0.1610	0.0528	0.0165	0.00690	0.00337	0.00138	0.000700
11	0.1588	0.0505	0.0160	[illegible]	0.00323	0.00128	0.000694
12	0.1567	0.0513	0.0150	0.00651	0.00311	0.00128	0.000676
13	0.1588	0.0498	0.0151	0.00636	0.00312	0.00130	0.000700
15	0.1548	--	0.0142	0.00594	0.00278	0.00125	0.000711
17	0.1548	--	0.0140	0.00564	0.00278	0.00127	--
19	0.1533	--	0.0138	0.00557	0.00270	0.00131	--
21	0.1571	--	0.0135	0.00535	0.00246	0.00129	--

[a]Turbidity at 436 mμ.

[b]Concentration in FTU, where 1 FTU equals 0.8 mg. per liter of reactants.

[c]Concentration in ppm of reactants.

TABLE XXI

Turbidity[a] in cm.$^{-1}$ of Formazin Suspensions

Conc.[b]	1000	500	200	100	50	20	10
Conc.[c]	800	400	160	80	40	16	8
Age in [redacted]							
0	0.1750	0.0580	0.0177	0.00800	0.00385	0.001510	0.000770
2	0.1720	0.0527	0.0144	0.00626	0.00287	0.000846	0.000488
4	0.1725	0.0523	0.0134	0.00560	0.00178	0.000540	0.000402
6	0.1720	0.0523	0.0124	0.00452	0.00136	0.000349	0.000286
8	0.1701	0.0514	0.0118	0.00453	0.00104	0.000238	0.000225
10	0.1701	0.0520	0.0108	0.00429	0.000899	0.000243	0.000238
12	0.1725	0.0523	0.00992	0.00404	--	0.000244	0.000244

[a]Turbidity at 436 mμ.

[b]Concentration in FTU where 1 FTU equals 0.8 mg. per liter of reactants.

[c]Concentration in ppm of reactants.

TABLE XXII

Turbidity[a] in cm.$^{-1}$ of Formazin Suspensions

Conc.[b]	1000	500	200	100
Conc.[c]	800	400	160	80
Age in Weeks				
0	0.1786	0.0598	0.0186	0.00837
2	0.1750	0.0558	0.0167	0.00759
3	0.1701	0.0538	0.0160	0.00726
8	0.1631	0.0519	0.0148	0.00687
12	0.1610	0.0514	0.0146	0.00627

[a]Turbidity at 436 mμ.

[b]Concentration in FTU, where 1 FTU equals 0.8 mg. per liter of reactants.

[c]Concentration in ppm of reactants.

TABLE XXIII

Turbidity[a] in cm.$^{-1}$ of Formazin Suspensions

Conc.[b]	1000	500	200	100	50	20	10
Conc.[c]	800	400	160	80	40	16	8
Age in [redacted]							
0	0.1753	0.0576	0.0167	0.00824	0.00392	0.001480	0.000738
7	0.1588	0.0498	0.0149	0.00624	0.00278	0.000400	0.000336
14	0.1565	0.0494	0.0146	0.00562	0.00249	0.000176	0.000193
21	0.1515	0.0463	0.0129	0.00487	0.00200	0.000168	0.000131

[a]Turbidity at 436 mμ.

[b]Concentration in FTU, where 1 FTU equals 0.8 mg. per liter of reactants.

[c]Concentration in ppm of reactants.

Turbidity[a] in $cm.^{-1}$ of Ludox Suspensions

Conc. in ppm Ludox[b]	30000	15000	7500	3000	1500	750	300
Age in Weeks							
1	0.0448	0.0269	0.0159	0.00773	0.00435	0.00254	0.00113
2	0.0445	0.0266	0.0159	0.00775	0.00447	0.00254	0.00115
4	0.0451	0.0269	0.0162	0.00785	0.00445	0.00260	0.00113
6	0.0466	0.0275	0.0167	0.00808	0.00464	0.00256	0.00113
8	0.0461	0.0283	0.0168	0.00823	0.00478	0.00265	0.00121
10	0.0465	0.0288	0.0170	0.00840	0.00472	0.00268	0.00115
12	0.0462	0.0288	0.0168	0.00840	0.00467	0.00259	0.00115

[a]Turbidity at 436 mμ.

[b]These concentrations of Ludox are required to produce turbidity values similar to those from the polystyrene latex suspensions.

TABLE XXV

Turbidity[a] in $cm.^{-1}$ of Stabilised[b] Ludox Suspensions

Conc. in ppm Ludox[c]	30000	15000	7500	3000	1500	750	300
Age in Weeks							
1	0.0946	0.0543	0.0288	0.0118	0.00611	0.00301	0.00113
2	0.0976	0.0556	0.0295	0.0124	0.00624	0.00298	0.00115
4	0.0976	0.0556	0.0292	0.0124	0.00618	0.00318	0.00119
6	0.1028	0.0585	0.0299	0.0127	0.00637	0.00321	0.00125
8	0.1078	0.0589	0.0311	0.0130	0.00661	0.00348	0.00137
10	0.1118	0.0599	0.0310	0.0139	0.00667	0.00366	0.00145
12	0.1159	0.0602	0.0306	0.0143	0.00697	0.00489	0.00150

[a]Turbidity at 436 mμ.

[b]Stabilising agent was 0.05 g NaCl.

[c]These concentrations of Ludox are required to produce turbidity values similar to those from the polystyrene latex suspensions.

TABLE XXVI

Turbidity[a] in cm.$^{-1}$ of 88 mμ Diameter Polystyrene Latex Suspensions

Conc. in [illegible] of P. Latex	26.00	10.40	5.20	2.60	1.04	0.52	0.26
Age in Weeks							
0	0.1342	0.0487	0.0237	0.0120	0.00480	0.00252	0.00125
1	0.1334	0.0485	0.0237	0.0119	0.00483	0.00246	0.00125
3	0.1326	0.0489	0.0236	0.0119	0.00488	0.00248	0.00126
5	0.1340	0.0492	0.0238	0.0118	0.00479	0.00248	0.00128
7	--	0.0500	0.0242	0.0120	0.00487	0.00252	0.00126
9	--	0.0498	0.0239	0.0120	0.00490	0.00250	0.00128
11	--	0.0490	0.0238	0.0118	0.00483	0.00252	0.00130
13	--	--	0.0235	0.0119	0.00472	0.00246	0.00130

[a]Turbidity at 436 mμ.

TABLE XXVII

Turbidity[a] in cm.$^{-1}$ of 88 mμ Diameter Polystyrene Latex Suspensions

Conc. in ppm of P. Latex	29.00	11.15	5.80	2.90	1.12	0.58	0.29
Age in Weeks							
0	0.1589	0.0579	0.0275	0.0137	0.00552	0.00286	0.00140
2	0.1610	0.0589	0.0276	0.0138	0.00551	0.00270	0.00142
4	0.1632	0.0590	0.0280	0.0139	0.00558	0.00196	0.00152
6	0.1589	0.0574	0.0274	0.0138	0.00560	0.00168	0.00144
8	0.1579	0.0579	0.0272	0.0138	0.00552	0.00154	0.00142
10	0.1568	0.0574	0.0272	0.0135	0.00548	0.00152	0.00139
12	0.1568	0.0565	0.0272	0.0134	0.00536	--	0.00141

[a] Turbidity at 436 mμ.

[redacted]

Turbidity[a] in cm.$^{-1}$ of 188 mμ Diameter Polystyrene Latex Suspensions

Conc. in [redacted] of P. Latex	13.71	6.86	2.74	1.37	0.68	0.27	0.14
Age in [redacted]							
0	0.2978	0.1148	0.0405	0.0194	0.00962	0.00380	0.00191
2	0.2978	0.1148	0.0405	0.0192	0.00931	0.00373	0.00183
4	0.2978	0.1162	0.0410	0.0195	0.00929	0.00368	0.00178
6	0.3050	0.1164	0.0405	0.0195	0.00946	0.00368	0.00171
8	0.2978	0.1156	0.0402	0.0190	0.00916	0.00354	0.00160
10	0.2978	0.1113	0.0395	0.0186	0.00906	0.00347	0.00147
12	0.2978	0.1102	0.0395	0.0185	0.00903	0.00348	0.00156

[a]Turbidity at 436 mμ.

Turbidity[a] in cm.$^{-1}$ of 138 mμ Diameter Polystyrene Latex Suspensions

Conc. in [illegible] of P. Latex	13.45	6.72	2.68	1.34	0.67	0.27	0.13
Age in Weeks							
0	0.2650	0.1055	0.0375	0.0177	0.00887	0.00352	0.00176
2	0.2690	0.1046	0.0378	0.0176	0.00888	0.00353	0.00180
4	0.2710	0.1046	0.0376	0.0175	0.00890	0.00356	0.00180
6	0.2570	0.1024	0.0370	0.0173	0.00869	0.00354	0.00173
8	0.2592	0.1020	0.0363	0.0170	0.00836	0.00345	0.00172
10	0.2538	0.1019	0.0363	0.0169	0.00857	0.00350	0.00173
12	0.2538	0.0992	0.0363	0.0166	0.00846	0.00341	0.00169

[a]Turbidity at 436 mμ.

TABLE XXX

Turbidity[a] in $cm.^{-1}$ of 264 mμ Diameter Polystyrene Latex Suspensions

Conc. in ppm of P. Latex	5.50	2.75	1.10	0.55	0.28	0.11	0.06
Age in Weeks							
0	0.2130	0.0610	0.0163	0.00688	0.00318	0.00122	0.000620
2	0.2130	0.0612	0.0160	0.00685	0.00311	0.00122	0.000624
4	0.2130	0.0610	0.0160	0.00672	0.00313	0.00122	0.000638
6	0.2130	0.0621	0.0161	0.00685	0.00313	0.00124	0.000638
8	0.2130	0.0614	0.0158	0.00669	0.00301	0.00118	0.000604
10	0.2092	0.0596	0.0152	0.00642	0.00295	0.00116	0.000590
12	0.2074	0.0596	0.0153	0.00645	0.00295	0.00116	0.000596

[a]Turbidity at 436 mμ.

TABLE XXXI

Turbidity[a] in $cm.^{-1}$ of 264 mμ Diameter Polystyrene Latex Suspensions

Conc. in ppm of P. Latex	5.44	2.72	1.08	0.54	0.27	0.11	0.05
Age in Weeks							
0	0.2164	0.0615	0.0162	0.00695	0.00322	0.00122	0.000606
2	0.2225	0.0619	0.0155	0.00666	0.00380	0.00124	0.000624
4	0.2204	0.0623	0.0151	0.00642	0.00334	0.00127	0.000648
6	0.2204	0.0628	0.0147	0.00616	0.00324	0.00122	0.000610
8	0.2184	0.0618	0.0140	0.00604	0.00319	0.00123	0.000610
10	0.2204	0.0615	0.0137	0.00609	0.00321	0.00119	0.000604
12	0.2130	0.0609	0.0135	0.00616	0.00317	0.00117	0.000592

[a]Turbidity at 436 mμ.

TABLE XXXII

Turbidity[a] in $cm.^{-1}$ of 365 mμ Diameter Polystyrene Latex Suspensions

Conc. in ppm of P. Latex	10.00	4.90	2.45	0.98	0.49	0.24	0.10	0.05
Age in Weeks								
0	0.373	0.0745	0.0233	0.00661	0.00304	0.00143	0.000580	0.000306
1	0.373	0.0735	0.0228	0.00669	0.00306	0.00141	0.000590	0.000318
3	0.361	0.0719	0.0220	0.00646	0.00301	0.00138	0.000600	0.000314
4	0.373	0.0718	0.0224	0.00646	0.00306	0.00135	0.000560	0.000329
6	0.378	0.0718	0.0220	0.00638	0.00303	0.00129	0.000600	0.000309
8	0.361	0.0710	0.0220	0.00645	0.00315	0.00123	0.000624	0.000382
10	0.361	0.0679	0.0216	0.00645	0.00317	0.00107	0.000676	0.000368
12	0.380	0.0683	0.0221	--	0.00337	0.00100	0.000705	0.000364

[a]Turbidity at 436 mμ.

TABLE XXXIII

Turbidity[a] in $cm.^{-1}$ of 365 mμ Diameter Polystyrene Latex Suspensions

Conc. in ppm of P. Latex	3.29	1.65	0.66	0.33	0.16	0.07	0.03
Age in Weeks							
0	0.0402	0.0136	0.00439	0.00202	0.000960	0.000492	0.000223
2	0.0407	0.0138	0.00422	0.00209	0.000980	0.000382	0.000224
4	0.0409	0.0137	0.00433	0.00206	0.001020	0.000465	0.000262
6	0.0403	0.0137	0.00431	0.00203	0.001000	0.000421	0.000251
8	0.0392	0.0133	0.00427	0.00197	0.000980	0.000414	0.000256
10	0.0392	0.0133	0.00433	0.00194	0.001290	0.000412	0.000260
12	—	0.0133	0.00439	0.00197	0.000970	0.000401	0.000270

[a]Turbidity at 436 mμ.

Turbidity[a] in $cm.^{-1}$ of 557 mμ Diameter Polystyrene Latex Suspensions

Conc. in ppm of P. Latex	6.50	3.25	1.30	0.69	0.33	0.13	0.06
Age in Weeks							
0	0.0593	0.0174	0.00502	0.00225	0.00109	0.000426	0.000217
2	0.0600	0.0166	0.00498	0.00222	0.00105	0.000426	0.000227
4	0.0585	0.0165	0.00490	0.00220	0.00104	0.000436	0.000252
6	0.0580	0.0164	0.00490	0.00220	0.00104	0.000414	0.000233
8	0.0561	0.0163	0.00480	0.00215	0.00102	0.000410	0.000247
10	0.0559	0.0168	0.00476	0.00215	0.00100	0.000408	0.000265
12	0.0551	0.0168	0.00487	0.00213	0.00101	0.000394	0.000287

[a]Turbidity at 436 mμ.

Turbidity[a] in $cm.^{-1}$ of 557 mμ Diameter Polystyrene Latex Suspensions

Conc. in ppm of P. Latex	6.10	3.05	1.22	0.61	0.30	0.12	0.06
Age in Weeks							
0	0.0519	0.0155	0.00469	0.00208	0.000963	0.000466	0.000212
2	0.0531	0.0157	0.00464	0.00217	0.000813	0.000432	0.000211
4	0.0523	0.0156	0.00456	0.00217	0.000704	0.000426	0.000162
6	0.0502	0.0147	0.00439	0.00223	0.000616	0.000371	0.000102
8	0.0496	0.0144	0.00433	0.00261	0.000666	0.000342	0.000139
10	0.0496	0.0127	0.00430	0.00269	0.000610	0.000352	0.000128
12	0.0488	--	0.00430	--	0.000610	0.000336	0.000139

[a]Turbidity at 436 mμ.

TABLE XXXVI

Turbidity[a] in $cm.^{-1}$ of 814 mμ Diameter Polystyrene Latex Suspensions

Conc. in ppm of P. Latex	8.64	4.32	1.72	0.86	0.43	0.17	0.09
Age in Weeks							
0	0.2240	0.0596	0.0159	0.00699	0.00331	0.00125	0.000639
2	0.1242	0.0557	0.0155	0.00674	0.00299	0.00115	0.000560
4	0.1092	0.0543	0.0154	0.00666	0.00262	0.00114	0.000510
6	0.0795	0.0574	0.0153	0.00672	0.00273	0.00113	0.000476
8	0.0562	0.0574	0.0146	0.00659	0.00257	0.00109	0.000426
10	0.0889	0.0579	0.0142	0.00659	0.00257	0.00109	0.000438
12	0.0895	0.0585	0.0140	0.00612	0.00232	0.00103	0.000438

[a]Turbidity at 436 mμ.

TABLE XXXVII

Turbidity[a] in $cm.^{-1}$ of 814 mμ Diameter Polystyrene Latex Suspensions

Conc. in ppm of P. Latex	7.66	3.83	1.54	0.77	0.38	0.15	0.08
Age in Weeks							
0	0.1890	0.0519	0.0141	0.00621	0.00292	0.00172	0.000580
2	0.1725	0.0500	0.0119	0.00576	0.00213	0.00162	0.000476
4	0.1701	0.0505	0.0088	0.00599	0.00194	0.00160	0.000488
6	0.1679	0.0496	0.0120	0.00576	0.00176	0.00152	0.000408
8	0.1442	0.0509	0.0114	0.00591	0.00158	0.00141	0.000466
10	0.1507	0.0514	0.0119	0.00588	0.00147	0.00149	0.000426
12	0.1471	--	0.0121	0.00592	0.00138	0.00147	0.000492

[a]Turbidity at 436 mμ.

TABLE XXXVIII

Turbidity[a] in $cm.^{-1}$ of 1171 mμ Diameter Polystyrene Latex Suspensions

Conc. in ppm of P. Latex	6.50	3.25	1.30	0.65	0.32	0.13	0.06
Age in Weeks							
0	0.0527	0.01733	0.00532	0.00243	0.00118	0.000463	0.000260
2	0.0506	0.01344	0.00447	0.00189	0.00107	0.000360	0.000194
4	0.0486	0.01204	0.00375	0.00139	0.00105	0.000352	0.000169
6	0.0461	0.01074	0.00359	0.00113	0.00104	0.000287	0.000138
8	0.0453	0.00954	0.00327	0.00100	0.00084	0.000295	0.000106
10	0.0451	0.00969	0.00304	0.00113	0.00105	0.000278	0.000109
12	0.0451	0.01034	0.00282	0.00122	---	0.000320	0.000125

[a]Turbidity at 436 mμ.

TABLE XXXIX

Turbidity[a] in $cm.^{-1}$ of 1171 mμ Diameter Polystyrene Latex Suspensions

Conc. in ppm of P. Latex	5.88	2.96	1.18	0.59	0.29	0.12	0.06
Age in Weeks							
0	0.0434	0.0146	0.00466	0.00217	0.001031	0.000412	0.000228
2	0.0400	0.0144	0.00461	0.00195	0.000958	0.000427	0.000255
4	0.0395	0.0145	0.00456	0.00185	0.000819	0.000448	0.000260
6	0.0372	0.0140	0.00444	0.00175	0.000710	0.000390	0.000206
8	0.0378	0.0138	0.00433	0.00179	0.000480	0.000378	0.000190
10	0.0375	0.0139	0.00436	0.00166	0.000352	0.000374	0.000215
12	0.0381	0.0133	0.00436	0.00167	0.000306	0.000374	0.000220

[a]Turbidity at 436 mμ.

TABLE XL

Refractive Index Differences of Turbid Suspensions at 436 mμ

Material	Conc. in ppm	Difference[a]
Polystyrene Latex-88	29.00	0.0000090
Polystyrene Latex-188	13.45	0.0000043
Polystyrene Latex-264	5.44	0.0000024
Polystyrene Latex-365	3.29	0.0000009
Polystyrene Latex-557	6.10	0.0000027
Polystyrene Latex-814	7.66	0.0000040
Polystyrene Latex-1171	5.88	0.0000057
Formazin	800.00	0.0000080
Fullers Earth	34.00	0.0000068
Voleloy	80.00	0.0000072

[a]Refractive index difference from triply distilled water.

BIOGRAPHICAL SKETCH

Anne Ayres Terry was born on July 1, 1936, in Atlanta, Georgia. In 1941 she traveled with her parents to the Panama Canal Zone. In 1942 she returned to the United States to Acadia Parish, Louisiana, where she attended grammar school. In 1946 the family made their home in Mobile, Alabama, and in 1953 she graduated from Murphy High School with very high honors.

In 1957 she received the B. A. degree from Agnes Scott College with a double major in chemistry and mathematics.

In September, 1957, she entered Graduate School in the Department of Chemistry at the University of Florida. From September, 1957, to June, 1959, she held a graduate assistantship in teaching. From June, 1959, to August, 1961, she held a research assistantship sponsored by the National Institutes of Health.

The author is a member of the American Chemical Society, Gamma Sigma Epsilon Chemical Fraternity, and Chi Beta Phi Scientific Fraternity.

This dissertation was prepared under the direction of the chairman of the candidate's supervisory committee and has been approved by all members of that committee. It was submitted to the Dean of the College of Arts and Sciences and to the Graduate Council, and was approved as partial fulfillment of the requirements for the degree of Doctor of Philosophy.

August 12, 1961

Dean, College of Arts and Sciences

Dean, Graduate School

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